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Natural flood management - an Ecosystem based Adaptation response for climate change

Iacob, Oana

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Natural flood management – an Ecosystem based Adaptation response for climate change

By

Oana Iacob BSc MSc

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School of the Environment
University of Dundee
United Kingdom

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Contents

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Declaration

The material contained in the thesis has not been previously submitted for a higher degree in this or any other institution. Unless otherwise stated, all references have been consulted by the author. The work of which the thesis is a record has been done by the author except where otherwise acknowledged.

Oana Iacob

Abstract

Climate change is one of the most pressing issues facing civil society. Scientific evidence indicates the likelihood of greater variability and more frequent extremes of temperature and precipitation which will result in increased flood risk and corresponding social, economic and environmental impacts. Complementing more traditional structurally-based engineering interventions, an important additional adaptation strategy is through natural flood management (NFM). NFM seeks to utilise natural processes (i.e. by promoting higher infiltration through land management practices) to attenuate flood peaks. Such measures have wider significance in the context of Ecosystem based Adaptation (EbA), to deliver highly beneficial solutions as they provide important benefits in relation to runoff rates but also in terms of wider environmental aspects (e.g. water quality, biodiversity).

The present study used a holistic approach to evaluate the effectiveness of NFM options in reducing the flood risk for the current and future climate with a consideration also for the wider delivery of ecosystem services. Tarland Burn catchment (NE Scotland) was used as a platform to explore individual adaptation options through woodland expansion (distinguishing between coniferous and deciduous) and drainage schemes, together with land use scenarios that explore emergent socio-economic contexts. The distributed hydrological model WaSiM-ETH was utilised for the analysis linking land management options with climate projections obtained from UK Climate Projections (UKCP09).

Modelling results showed that the magnitude of extreme weather events is expected to increase up to the end of the century with important implications for climate adaptation strategies. Woodland expansion could help attenuate the high flows, with the benefit for flood protection significantly higher for coniferous woodland compared to deciduous woodland and up to 1.5 more if woodland is located in lowland areas. However, modelling results suggested that there are potential negative impacts of afforestation on low flows (and hence water quality) which could exacerbate existing vulnerabilities. This may become an even greater issue in the future as summers are predicted to be drier and warmer. Improving the efficiency of the drainage network was seen to reduce the high flows, though the results are marginal for the winter when most floods occur. Modelling results suggested that climate change will eventually exceed the capacity of beneficial land use change by itself (through NFM measures) to avoid significant

changes on catchment hydrology. This has important implications as other complementary engineered solutions may therefore be required to counteract the adverse impacts of climate change on flood risk. Moreover, the EbA assessments results indicated that NFM options may not always be ‘win-win’ solutions as commonly advertised (McShane *et al.*, 2011). Instead trade-offs between the delivery of different services may be required and decisions should be aimed at maximizing benefits whilst minimizing the disbenefits. This novel approach highlighted that land use change should be carefully managed and the choices about land use and flood risk should always have at their core an enhancement of landscape resilience, particularly at the catchment scale.

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Abbreviations

AM	Annual Maxima
ArcGIS	Arc Geographical Information System
CBD	Convention on Biological Diversity
CCRA	Climate Change Risk Assessment
DEM	Digital Elevation Model
DHI	Danish Hydrological Institute
EbA	Ecosystem based Adaptation
ESRI	Environmental Systems Research Institute
ETH	Eidgenössische Technische Hochschule
EU	European Union
FDCs	Flow Duration Curve
FEH	Flood Estimation Handbook
GIS	Geographic Information System
GLUE	Generalised Likelihood Uncertainty Estimation
HRUs	Hydrological Response Units
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
LCM2007	Land Cover Map 2007
MA	Millennium Ecosystem Assessment
Met Office	Meteorological Office
NEA	National Ecosystem Assessment
NFM	Natural Flood Management
NSE	Nash-Sutcliffe Efficiency
PES	Payment for Ecosystem Services
PEST	Parameter Estimation Tool
PET	Potential Evapotranspiration
POT	Peak Over Threshold
PREVAH	Precipitation Runoff Evapotranspiration Hydrotope
PTF	Pedo-Transfer Function
RHESSys	Regional Hydro-Ecological Simulation System
SAIFF	Scottish Advisory and Implementation Forum for Flooding
SEPA	Scottish Environment Protection Agency

SNH	Scottish Natural Heritage
SRES	Special Report on Emission Scenarios
SWAT	Soil Water Assessment Tool
Tanalys	Topographical Analysis
TFPS	Tarland Flood Prevention Scheme
UK	United Kingdom
UKCP09	UK Climate Projections
UNCCD	United Nations Convention to Combat Desertification
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme
USA	United States of America
VIC	Variable Infiltration Capacity
WaSiM	Water Flow and Balance Simulation Model
WFD	Water Framework Directive

Chapter 1. Introduction

1.1 Research context

Climate change is projected to alter precipitation patterns and hence river flows and the magnitude/frequency characteristics of floods and droughts. The global climate is expected to change at a rate unprecedented in human history, as exemplified by rising sea levels, glacial retreat, changing precipitation patterns and an increasing frequency of extreme weather events (Kiehl, 2011). Evidence for these changes, which include both short-term climatic variability and longer term trends, underpins the need for a twin-track response, involving both mitigation and adaptation strategies (Perez *et al.*, 2010). With regard to adaptation, the primary goal is to reduce exposure to natural hazards such as flooding, whilst increasing human resilience to hazard-related events from the local scale upwards and reduce vulnerability e.g. by not building/living on floodplains (Tschakert & Dietrich, 2010). Evidence increasingly demonstrates that local flood risk must be viewed as non-stationary. Risks vary in direct response to changing hydroclimatic drivers, but also to indirect controls on runoff generation and flow routing, as a consequence of catchment land use changes and hydromorphological alterations to the channel network (Werritty *et al.*, 2006).

Traditional approaches to flood control have emphasised ‘hard’ engineering ‘solutions’, mainly centred around protection of high value infrastructure. These are also widely emplaced to defend agricultural production on drained wetlands and floodplains. These schemes often have significant environmental impacts because they disrupt natural flows and storage processes. Moreover, whilst engineered strategies are generally designed to provide protection for specific flood levels (based on an inferred recurrence interval), maintaining the same level of protection under changing climatic conditions requires upgrading defences (potentially repeatedly) with attendant economic, social and environmental costs. Thus, there is a pressing need to develop improved adaptation strategies centred on sustainable natural resources, and for catchment land-based flood management measures rather than just hard engineering, in order to provide greater resilience against the anticipated increased frequency of extreme events (Campbell *et al.*, 2009; Heller & Zavaleta, 2009).

Ecosystem based Adaptation (EbA) is an emerging paradigm for managing natural resources under increasingly variable and perturbed climatic conditions. EbA aims to enhance the natural dynamic and resilient properties of ecosystems to buffer the adverse impacts of climate change, and therefore reduce human vulnerability (Colls *et al.*, 2009). The need for interdisciplinary perspectives in adaptation planning, including social science, was emphasised by Heller & Zavaleta (2009). In particular, EbA recognises that the future is intrinsically uncertain due to climate change and associated pressures (e.g. spread of invasive species), and that the most effective strategies to reduce risk therefore include measures to improve system resilience, rather than being predicated on a particular outcome.

An exemplar of EbA, natural flood management (NFM) options are emerging as a novel way to reduce the flood risk when considered within the wider context of multiple benefits (i.e. benefits go beyond flood alleviation in providing a wide range of ecosystem services). NFM measures emphasize the restoration of innate hydrological pathways, providing important regulating functions in relation to both runoff rates and water quality. They are heralded as a potentially important climate change adaptation strategy. In the United Kingdom (UK) there is a policy interest in NFM-type measures, for example, with the introduction of the European Union (EU) Floods Directive implemented in Scotland through the Flood Risk Management Act that encourages the use of sustainable approaches for flood attenuation wherever possible. However there is a higher degree of uncertainty related to the use of NFM, and more research is needed to understand how the associated measures work and the degree to which they present an efficient option (SEPA, 2012). Two types of NFM options that will be investigated in the present study are the planting of new woodland (afforestation) and modification of land drainage from man-made drainage schemes.

The capacity of afforestation options to attenuate flood risk has already been demonstrated in a series of studies (Andréassian, 2004; Nisbet & Thomas, 2006; Odoni & Lane, 2010). However, existing research suggests that afforestation options may have a less significant impact on the larger magnitude of extreme weather events. Most studies have recorded an effect on the peak flows for return periods of less than 5-10 years (Beschta *et al.*, 2000; Lane *et al.*, 2005; Sikka *et al.*, 2003) but the effect decreases for larger and more extreme events (van Dijk *et al.*, 2009). A study in the western Cascades of Oregon United States of America (USA) recorded very small impacts of forest treatment on peak flows for events larger than 5 years (Beschta *et al.*, 2000).

Existing research shows that the scale of afforestation has a large impact on the overall flood risk, e.g. in terms of a reduction in peak flows. A review by Calder et *al*. (2009) noted that more than 20% afforestation is required to achieve a significant effect on the flow peaks. A study in South America found that the impact of woodland cover on the peak discharge decreases as the magnitude of the rainfall events increase (Bathurst *et al.*, 2011a, b). It also suggested that noticeable results could be achieved if the catchment is afforested with more than 20-30%, particularly in large catchments (up to 1500 km^2). However, neither of these studies distinguished between the relative effect of coniferous and deciduous woodland in relation to different evapotranspiration and interception rates and their different seasonal effects.

The location of new woodland in the catchment is likely to impact on the efficiency in reducing high flows. A closer match might be expected between the water yields and the evapotranspiration rates in the lowlands, such that locating woodland there could have a more significant impact on flood peaks (Forestry Commission, 2005). As efforts for woodland expansion in Scotland continue, there is a need for a better understanding of both the scale of and spatial issues in relation to afforestation to achieve flood risk reduction.

Moreover, woodland expansion options were noted to alter the low flows that are particularly important in catchments for which drier summers are predicted in the future. As forest interception and transpiration rates increase, the baseflow levels decrease (Robinson *et al.*, 2003) leading to potential adverse impacts on aquatic ecology and water quality. Understanding the adverse impacts of afforestation options (i.e. reduction of the low flows) is important in achieving multiple benefits from EbA. How afforestation measures will perform under changing climatic conditions is not yet fully understood. A study by Calder *et al.* (2009) looked at four tree species in order to assess the changes in the evaporation using the UKCP02 scenarios. The results showed increased mean annual evaporation rates for three out of the four species studied, with impacts for the water yields particularly important in dry regions.

There is a long history of research investigating drainage issues, as land drainage is a common practice in UK. The role of land drainage is to remove water from the land to increase productivity; therefore it modifies hydro-pedological flow paths. Whilst some studies found that drainage decreases the flood peaks, others recorded an increase in flood peaks. Generally it is accepted that drainage is likely to decrease the flood risk, however the exact impact will depend on catchment and soil characteristics, flow and meteorological regime (Blanc *et al.*, 2012). Land drainage may still be required in some areas, as large agriculturally productive areas of the UK remain dependent on flood protection and land drainage (Wheater & Evans, 2009), especially as wetter winters are expected (Murphy *et al.*, 2009). More research is needed at the catchment scale to understand the likely impact of drainage practices, and to ensure that food production demands are met alongside adaptive flood risk management.

It is increasingly acknowledged that effective management of river basins under a changing climate requires the integration of both land use and climate change in hydrological assessments. Not only do climate change and land use affect catchment hydrology but these drivers are also changing together (with climate influencing land use) so there is a need to consider these two factors together, rather than separately, and to consider potential amplified effects. Some studies have modelled land use change (Bronstert *et al.*, 2007; Hundecha & Bárdossy, 2004; Niehoff *et al.*, 2002) and others climate change (Gädeke *et al.*, 2013; Steele-Dunne *et al.*, 2008) but very few have modelled both factors (Alaoui *et al.*, 2014; Bronstert, 2004).

Moreover, changes in land use go beyond the impact on the flood risk, to encompass a wide range of ecosystem services. The ecosystem services approach acknowledges the importance of nature in delivering benefits that are essential for human well-being (de Groot *et al.*, 2010). Woodland expansion options have the capacity to contribute in delivering a wide range of ecosystem services. However, whilst afforestation options have been critical in developing targets such as climate change mitigation, or protecting biodiversity, their potential for achieving a flood risk reduction has not been fully considered or integrated with these other objectives in an adaptation context because of the limited evidence.

This project aims to provide a better understanding of NFM approaches and their potential role as a climate change adaptation strategy, using the ecosystem services framework. Undertaking an EbA approach, the research presented in this thesis aims to increase the knowledge of the inter-dependencies and linkages that underpin the efficiency of different land use options for current and future climate, thus providing a holistic approach in the evaluation of NFM strategies. The research was undertaken using Tarland Burn catchment in NE Scotland, using a demonstration modelling approach from which it is possible to make generalizable conclusions.

1.2 Thesis structure

The framework for this thesis is presented in Figure 1.1, which includes an overview of the constituent chapters along with the substantive empirical evidence relevant to each step of the project. The thesis is structured in nine chapters, and a brief summary of each chapter is presented below.

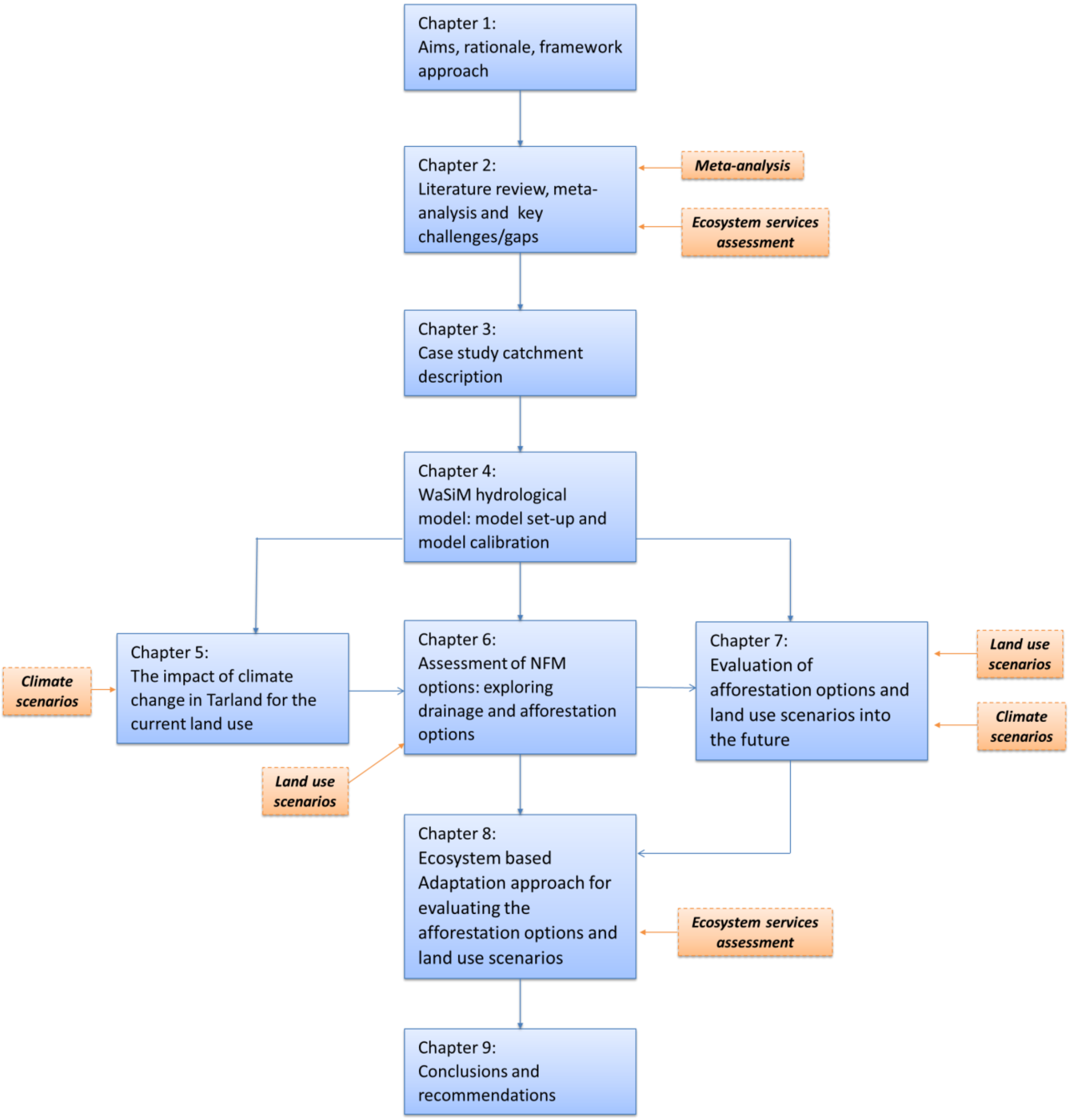

Figure 1.1. Chapter sequence and key deliverables of the thesis

Chapter 2 provides a critical examination of the current research and its relevance to the main topics underpinning this project: climate change, flood risk and ecosystem services. An overview of the main NFM options is provided, and the hydrological modelling approach is discussed. The results of a meta-analysis are presented, which helped inform the choice of NFM options at the centre of the study. The aims and objectives are set out at the end of the chapter, informed by the research gaps that were identified through literature review and the meta-analysis.

Chapter 3 consists of a description of the Tarland Burn study catchment in Aberdeenshire, Scotland. It provides an overview of the main catchment characteristics (land use, topography, geology) along with a discussion of the hydro-climatic aspects. Additionally, the data correction undertaken for the meteorological data is presented.

Chapter 4 provides an overview of the selection process for the principal modelling scheme used. The Water Flow and Balance Simulation Model (WaSiM-ETH) model spans as a complex model and was selected for its capacity to simulate forest hydrology and its appropriateness for climate investigations. An overview of the main equations and parameters used in the model to represent the main hydrological processes is also presented together with the model calibration and validation. The overall performance is examined, with consideration of model uncertainties.

In chapter 5 the impact of climate change on the magnitude of extreme weather events is explored. The chapter includes the methodology for the analysis and a discussion of recent climate trends and future climate in Scotland. The extreme rainfall events drawn from the UKCP09 Climate Projections are assessed for two event durations, with the impact on the discharge simulated using the WaSiM-ETH hydrological model. The results are discussed in the wider context of climate change, and including the implications for Tarland and beyond.

Chapter 6 examines several land use options in order to assess their effectiveness in reducing the high flows, and with a consideration for the low flows also, using a model simulation approach. The chapter presents the methodology and a description of the land options adopted for the investigation. Afforestation options were assessed in order to address scale and spatial issues in relation to NFM. The hydrological response was examined for four land use scenarios (i) World Markets, (ii) National Enterprise (iii) Global Sustainability and (iv) Local Stewardship. The scenarios are based on the IPCC

SRES driver framework (Nakicenovic *et al.*, 2000) and provide coherent and plausible interpretations of land use futures driven by different macro-drivers, policies and preferences (Brown & Castellazzi, 2014). The impact of improved drainage was assessed using a sensitivity testing approach, applied to the main parameter controlling the drainage flow in the model. A discussion is provided which explores the significance of the results in the target catchment, by linking it to previous research in the field.

Chapter 7 presents the model results for the interplay between land use and climate change scenarios, in order to increase the understanding of NFM option efficiencies under changing climatic conditions. This assessment presents a novel approach to climate investigations, by linking climate scenarios with land use scenarios in a hydrological model. The results are discussed and set into the context of the wider literature, as this applies to climate and land use research.

In chapter 8 an ecosystem services appraisal of the afforestation options and land use scenarios was undertaken. The EbA framework employed for the assessment is presented in the methodology section of this chapter. Opportunity maps for the afforestation options are provided. Furthermore, a comparison between woodland expansion options and improved drainage is presented from an ecosystem services delivery perspective. Critical trade-offs are presented in the discussion section, and are cross-referenced against policy priorities and targets.

In chapter 9 the conclusions and recommendations for further research are presented. The chapter draws together the main points from the discussion sections of each analysis chapter, and contextualizes the results. The strengths and weaknesses of the results are discussed along with sources of uncertainty. The second part of this final chapter examines the policy implications of the research and provides recommendations for further investigations in order to advance our knowledge in this research area.

1.3 Research aims and objectives

This thesis aims to provide a holistic approach for the evaluation of NFM options, considering their effectiveness for flood attenuation for the current and future climate and with a consideration for the delivery of ecosystem services. As already discussed in Chapter 1, extensive research has been undertaken to assess the impacts of land use (Brown & Castellazzi, 2014; Francés *et al.*, 2008; Krause *et al.*, 2007; Lin *et al.*, 2007;

Niehoff *et al.*, 2002) and climate change (Gädeke *et al.*, 2013; Kasei, 2009; Lehner *et al.*, 2006; Prudhomme *et al.*, 2010); however, there is a lack of coherent and consistent approaches that link both climate and land use change for flood risk management. Moreover, further work needs to be done to understand the benefits, disbenefits and trade-offs for ecosystem services in the implementation of NFM options (Blanc *et al.*, 2012).

The current research was funded by the Climate Centre for Expertise on Climate Change (ClimateXChange) which supports the Scottish Government by providing policy oriented research, advice and analysis. The project is part of the 'Climate change adaptation' underlying research team within the centre. Consequently, the project aims to generate policy relevant outputs informing the debate on the implementation of NFM options, as a climate change adaptation option. The current research is underpinned by SEPA's requirement for more research investigating the effectiveness of NFM options, with a focus on scale and spatial issues (SEPA, 2012). Moreover, the Scottish Government target for woodland expansion raises the question of where new woodland can bring the greatest number of benefits for ecosystem services. The acquired knowledge in the evaluation of NFM options should be useful to policy makers in a wide range of catchments. The conceptual framework of the project is presented in Figure 1.2.

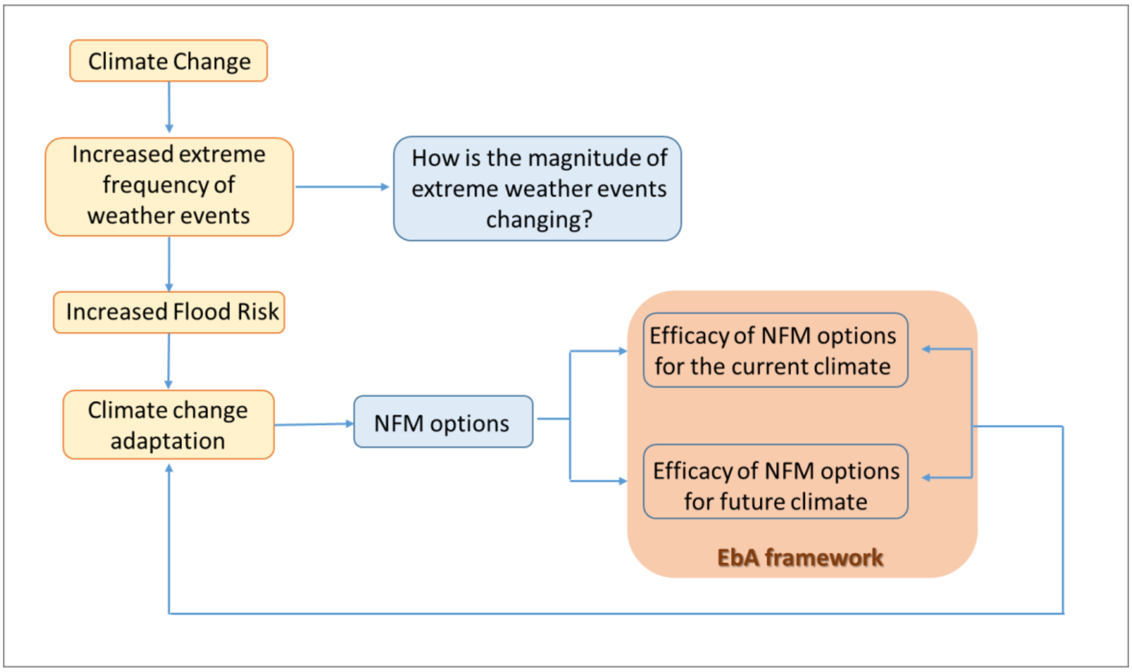

Figure 1.2. Conceptual framework

Given the gaps in the current research highlighted in Chapter 1, the project aims to assess the effectiveness of NFM options through woodland expansion, by increasing a catchments' resilience to current and future climate and to flood risk using an EbA framework.
To achieve this aim, five objectives have been set:

1. Understand how the climate is shifting the extreme weather events magnitude, up to the end of the century
2. Assess the effectiveness of NFM options for the current climate, with a focus on afforestation options and a consideration for improved drainage
3. Explore the hydrological impact of different land use scenarios based on socio-economic drivers, dictating the percentage of forest expansion
4. Increase the understanding of the interplay between land use options and future climate for catchment hydrology
5. Assess the potential for delivery of multiple benefits, by assessing NFM options using an EbA framework

The study uses a modelling approach to carry out the assessment, as this allows an exploration of different land use options by systematically integrating available knowledge in order to represent the main catchment processes. Moreover, climate change adaptation would not be possible without models, as they are the only way to explore potential futures (non-stationarity) which is required to inform adaptation policy.

Scenarios are being used in the present study to explore the consequences of different drivers of change (climate and socio-economic change) on land use and hence the feasibility of different options for climate change adaptation. The merits of the scenario approach have been widely acknowledged (Peterson *et al.*, 2003, Rounsevell *et al.*, 2006) as it provides a useful tool when key uncertainties render the prediction-based approach less reliable, as with aspects of future change.

Tarland Burn catchment was selected as a study case, to investigate the effectiveness of NFM options. The choice was informed by the availability of data and the catchment characteristics (i.e. land use, soils, average precipitation) making it a typical eastern Scottish catchment. Moreover the catchment has a long history of flooding, and it has been extensively drained.

Chapter 2. Literature review

2.1 Introduction

Climate change poses a threat to human well-being, because climate patterns are shifting and more extreme weather events are expected. A major consequence of climate change is the increased risk of flooding with severe environmental, social and economic impacts. Moving away from traditionally engineered interventions, NFM options have been suggested as potentially having considerable capacity to attenuate the flood risk, whilst also providing a wide range of other ecosystem services (Wheater *et al.*, 2010). However, whilst traditional engineered options have been extensively used, thus increasing an understanding of how they work, far less is known about how NFM options can deliver flood risk protection. Moreover, as the climate changes more research is now required to understand how effective this type of measure might be under future climates and what environmental benefits could be achieved that can contribute to creating more resilient communities.

2.2 Climate change evidence

Signs of a changing climate can be seen worldwide, from sea level rise to glacier melt, shifts in meteorological regimes and increased frequency of extreme weather events. The Physical Science Basis report of the Intergovernmental Panel on Climate Change - IPCC (IPCC, 2014a, b) is one of the most comprehensive, authoritative and widely-accepted statements of climate change. The Fifth Assessment Report states that human activities are the main contributing factor to the rise in CO_2 in the atmosphere, which plays a key role in global warming. Backing up this statement is evidence from the Antarctic and Greenland ice cores and direct measurement of CO_2 and global temperatures (Werritty & Sugden, 2013). Globally the climate system has become warmer by an average of 0.8 ^{o}C since the late 19th century and records demonstrate a rise of sea levels of an annual 1.8 mm since 1961 (Solomon *et al.*, 2007). The changes in climate extremes have a higher impact than the changes in the mean of a parameter, because it is more difficult to adapt to extremes (Katz & Brown, 1992; Werritty & Sugden, 2013). In Europe such extremes have included significant heatwaves and droughts, as well as devastating floods, with high economic and societal costs (Seneviratne *et al.*, 2006).

Recent climate trends in UK have been characterized by Barnett *et al.* (2006), partly updated by Jenkins *et al.* (2009) and reviewed specifically for Scotland by Werritty & Sugden (2013). Scotland has a very variable climate, but when averaged out over long periods of time, it has fewer extremes in temperature, rainfall and seasonality compared to continental Europe (Werritty & Sugden, 2013). The mean annual temperature in Scotland is spatially variable, between 4-9 ^{o}C, with mean rainfall totals ranging between 600-3000 mm (Barnett *et al.*, 2006). The average annual temperature in Scotland has increased by 1 ^{o}C and more annual precipitation was recorded (up to 60% more in winter in the north and west) since 1961. The frequency of extreme rainfall events has increased since 1961, however, there is a high degree of natural inter-annual and decadal variability in climate, which makes long term trends difficult to isolate (Werritty & Sugden, 2013).

Climate change projections rely on observed climate trends for their predictions. The UKCP09 Climate Projections are based on the latest scientific understanding and have been developed to assist decision makers in preparing for changes in climate (Murphy *et al.*, 2009). The projections describe how the climate is likely to change through to the end of the 21st century for different greenhouse gas emissions scenarios. They are the latest projections in a series from UKCIP dating back from 1998 and are based on three of the IPCC's (2000) Special Report on Emissions Scenarios – A1F1 (high), A1B (Medium) and B1 (Low). They include probabilities of different climate change outcomes rather than a deterministic outcome as with the previous versions. A Cumulative Distribution Function expresses the probability of climate change, as less or greater than a certain value. The 50% probability level in UKCP 09 is therefore a central estimate of a probability which is as likely as not to be exceeded. The 90% probability level represents the upper end of the model projections and the 10% probability level represents the lower end. This probabilistic approach offers the chance to adopt a risk based direction to planning and uncertainty, in order to support a more robust decision making process.

The UKCP09 projections are based on a model ensemble derived from the HadCM3 model and other international climate models. The probabilistic projections allow for the uncertainties that are inherent in the representation of major climate processes, as well as the effects of internal variability in the model outputs (Murphy *et al.*, 2009). The projections have been downscaled to 25 km resolution using the HadRM3 model. The HadRM3 model is not able to provide robust projections for resolutions under 24 hour time scale, but location-specific sub-daily estimates can be obtained from a Weather Generator (Jones *et al.*, 2009) that is based on the UKCP09 ensemble. The Weather Generator produces future scenarios by applying monthly change factors to observed statistics derived for each five kilometre grid cells across UK. UKCP09 projections have been used in a large number of hydrological studies (Bell *et al.*, 2012; Cloke *et al.*, 2010; Kay & Jones, 2012) to assess the likely response of catchments in the future.

The UK Climate Change Risk Assessment (CCRA) provides a comprehensive assessment of the likely impacts of climate change on different sectors in the UK (Defra, 2012a). Rowland & Fleck (2012) summarised the CCRA outputs for Scotland, which for some specific aspects differs from the rest of the UK. Several important risks have been identified for Scotland, along with a list of opportunities. Climate change will put a strain on Scotland's water resources, with the risk of drought expected to increase by 8%, as a result of higher summer soil deficits which will increase the need for crop irrigation. Low water levels will affect timber yield, with some conifer species the most affected. Species like Sitka Spruce will be the most impacted by droughts (Green & Ray, 2009; Petr *et al*., 2014; Ray *et al*., 2008).

The risk of inland flooding and coastal erosion is expected to increase, with adverse impacts on the quality and yield of crops. The UK CCRA suggests that agricultural land at risk of flooding is expected to increase by up to 100% by the 2050s, and by up to 170% by the 2080s, from the current baseline (Rowland & Fleck, 2012). Residential and non-residential properties could be 50% more at risk of flooding by the 2080s, with important economic, environmental and societal costs. Increased flooding could cause a rise in the number of injuries and mortality related to extreme weather events. Moreover it could increase the number of mental health patients, as some flood victims experience severe anxiety, depression and other similar conditions. Large areas of forest could be at risk of new and existing tree pests, leading to reduced timber production and negative impacts on woodland condition. Dry periods in the summer could reduce both the agricultural and timber yield, and increase the risk of wildfires by 30 to 40% through to the 2080s (Defra, 2012a; Rowland & Fleck, 2012).

The opportunities identified by the CCRA in Scotland include increased productivity of the land, as a result of drier summers and longer growing seasons, which can result in higher agricultural yields particularly for wheat and spring barley. Grassland productivity could benefit from the change in climate, as could productivity yields of some woodland types (Rowland & Fleck, 2012). This provides the opportunity to grow new crops and plant a range of new timber species, as the climatic conditions shift towards a warmer climate and longer growing seasons (Rowland & Fleck, 2012).

2.3 Flood risk management

Changes in the frequencies of extreme weather events is one of the most important consequences of climate change (Jones, 1999; Katz & Brown, 1992). Extreme flood events can have devastating impacts on the economy and ecology, and presents a risk to human life. Flooding affects large areas unconstrained by international boundaries. Whilst the most dramatic and extreme floods with considerable loss of human life occur outside Europe (Pinskwar *et al.*, 2012), particularly in South Asia, extreme floods have also affected Europe. The flood risk has increased across Europe during the last decade (Lehner *et al.*, 2006; Wilby *et al.*, 2008). Devastating floods in 2002, caused by the same meteorological event, affected a large region from Germany to the Czech Republic and from Romania to Russia. More recent floods occurred in 2005, 2007, 2010 and 2012 (Pinskwar *et al.*, 2012). Without further adaptation efforts, Europe is at high risk from both flooding and water shortages over the rest of the 21st century (IPCC, 2014c), which characterises the problem of extreme events.

In Scotland flood risk management was not regulated before the 20th century, with works for land improvement and flood protection carried out sporadically and solely for rural and urban and industrial development. Coordinated land management dates back to 1847, with the first Land Drainage (Scotland) Act setting procedures to mediate riparian landowner actions. Several land drainage policy frameworks have since been implemented, notably the Land Drainage (Scotland) Act 1930, updated in 1935 and 1941, and the Land Drainage (Scotland) Act 1958. These legislative actions help set in place a system of land drainage schemes for managing non-urban land (Spray *et al.*, 2009).

The Flood Prevention (Scotland) Act 1961 was developed to complement the Land Drainage (Scotland) Act 1958, by giving discretionary powers to local authorities to implement flood protection schemes for (mostly) urban areas. This legislative division between flood prevention works, carried out in urban and agricultural environments, caused conflicting schemes to be developed from early 1961 to the 1990s. While in rural areas the works were focused on drainage and river straightening, in urban areas they were focused on hard structural defences (Spray *et al.*, 2009). Thus, the sector lacked an integrated approach for flood management in which the whole catchment was seen as a unity, and such works often moved flood problems downstream.

Significant floods in the 1990s led to an amended Flood Prevention and Land Drainage (Scotland) Act 1997, placing a duty on local councils to survey and manage rivers that are at risk of generating floods on non-agricultural land. Whilst this piece of legislation was a step towards a more proactive approach, it still did not set an appropriate framework for an integrated catchment management (Spray *et al.*, 2009). The first time sustainable flood management has been established in legislation was with the introduction of the Water Environment and Water Services (Scotland) Act 2003.

In 2006 the first flood risk assessment and management directive was drafted by the European Union, prescribing approaches and procedures that should be met by member countries. The Flood Directive (European Commission, 2006) is influencing flood policy of member countries, by introducing a holistic and catchment oriented approach for managing flood risk. The EU Floods Directive represented a step forward, and away from the event-driven reactive approach based on structural engineered measures. The new changed vision of managing floods has seen approaches based on ‘room for rivers’, ‘living with floods’ and ‘working with nature’ (De Bruijin *et al.*, 2007).

The implementation of the Flood Risk Management (Scotland) Act in 2009 marked a shift in the way floods have been regulated in Scotland. The Act translates the European Flood Directive, by introducing a holistic framework to floods management. The change in the name points to the shift in the way in which the Scottish Government approaches flooding, by acknowledging that floods cannot be fully prevented but that flood protection can be achieved (Spray *et al.*, 2009).

The Scottish National Flood Risk Assessment developed by the Scottish Environmental Protection Agency (SEPA, 2011) reported that currently 1 in 11 of all residential properties and 1 in 13 of all non-residential properties are at risk of flooding, with an annual estimated average of overall damage to homes, businesses and arable land of between £ 720 million and £ 850 million. The change in landscape design over time are summarized in Figure 2.1 (O'Connell *et al.*, 2007), reflecting the progression of legislation and consequences for land management during the past century and through to the present day.

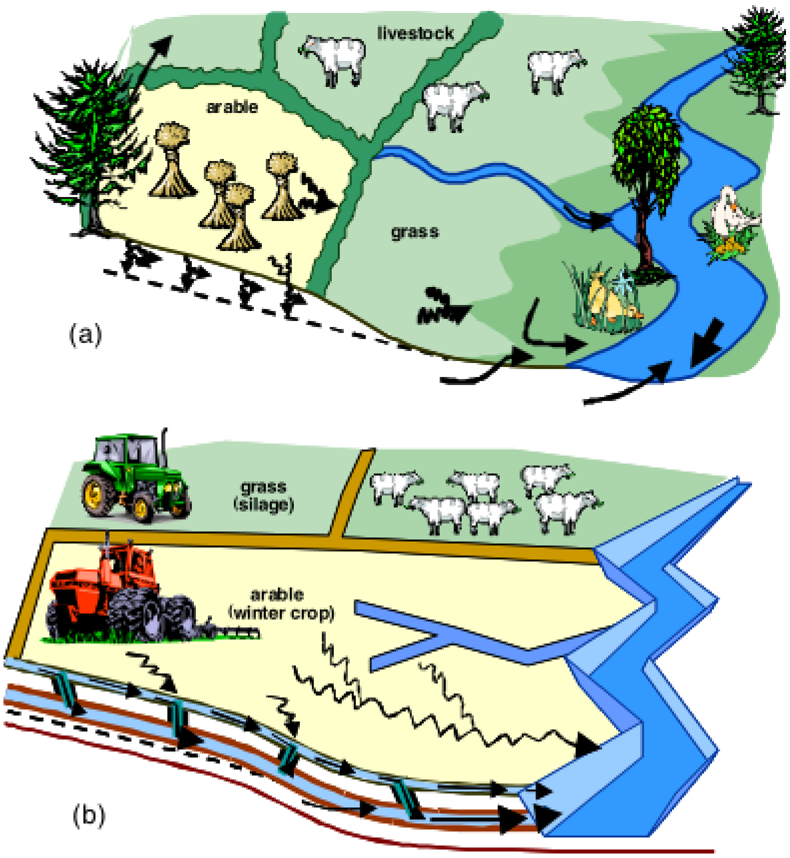

Figure 2.1. Agricultural landscape at a) the beginning of the 19th century and b) recent time (O'Connell *et al.*, 2007)

2.4 Natural flood management

Natural Flood Management options are defined as 'flood management techniques that aim to work with the natural processes (or nature)' to manage the flood risk (SEPA, 2012). NFM is widely recognised as an option in reducing flooding, whilst achieving multiple benefits throughout the catchment. It is rising rapidly up the policy agenda across Europe, especially because of its potential to buffer the effects of climate change (Wheater *et al.*, 2010). Natural processes comprise a wide range of strategies, varying from heavily modified to semi-natural options, with the type of intervention dictating the level of connection to the floodplain (see Figure 2.2).

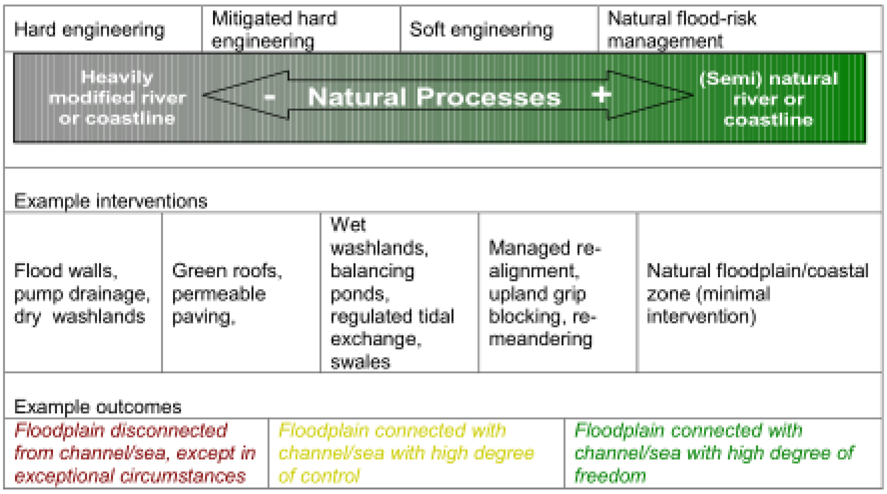

Figure 2.2. Conceptual model for natural processes strategies (Environment Agency, 2010)

Traditional hard (and indeed soft) engineering solutions are generally location specific measures that are applied to protect social and infrastructural assets at risk of flooding. These measures are designed to gain protection for certain flood events under assumed stationarity in the magnitude/frequency relationship (Figure 2.3a). Clearly, they become less effective, i.e. risks increase, under non-stationary conditions symptomatic of climate change (Figure 2.3b). By comparison, the introduction of NFM measures potentially provides greater adaptive capacity to negate climate change, by re-naturalising flows or at least providing a buffer against subsequent regime changes as NFM systems naturally adjust to changes in drivers through time (Figures 2.3c, d). However, the performance of NFM will ultimately be dependent on specific site conditions, inclusive of landscape setting, catchment characteristics, the degree of hydromorphological alteration and the extent and appropriateness of the different measures adopted. Performance will also evolve or mature over time, meaning that flood risk should be constrained within an envelope of possible outcomes (Figure 2.3d) rather than based upon a specific deterministic outcome.

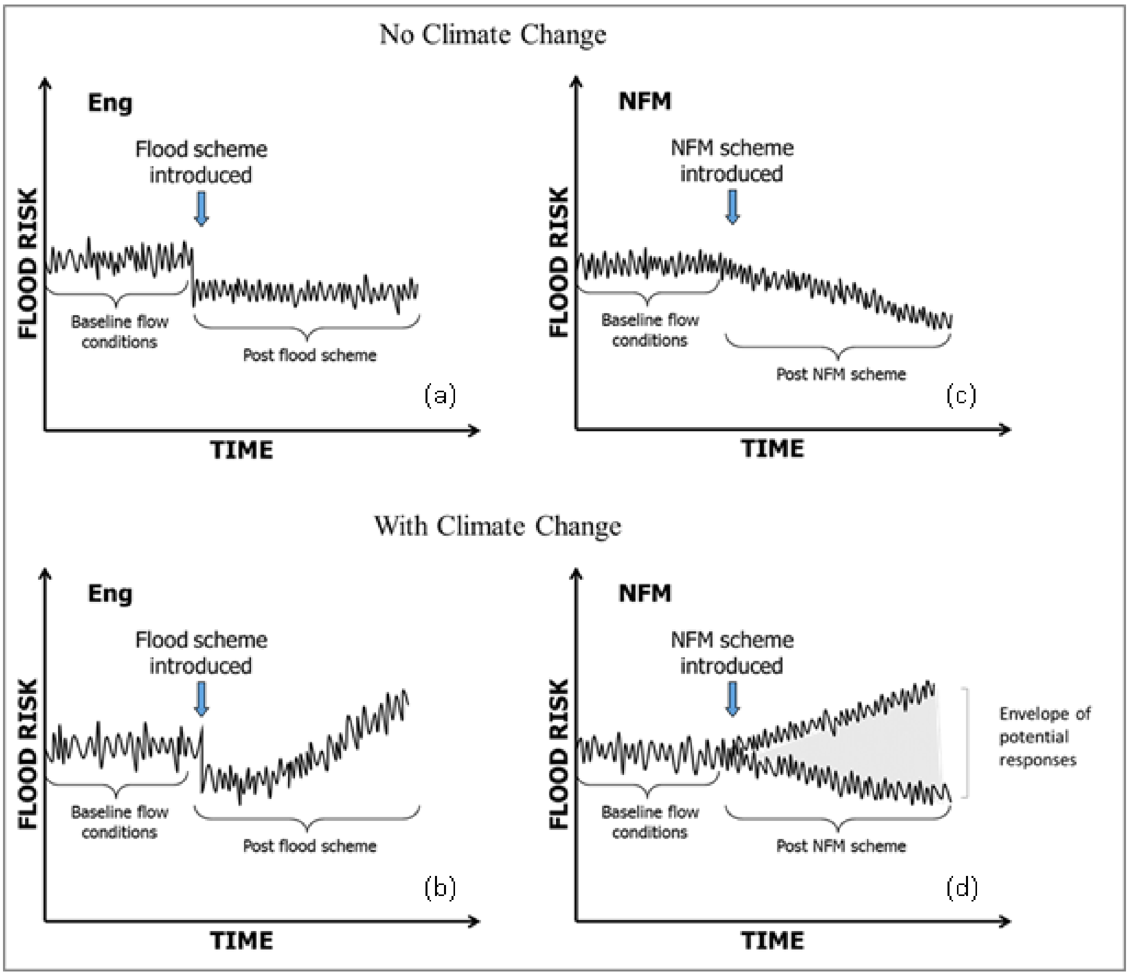

Figure 2.3. Representation of expected engineered (Eng) and NFM strategies behaviour in no climate change conditions and with climate change (Iacob *et al.*, 2014)

NFM involves the utilisation or restoration of 'natural' land cover and channel-floodplain features within catchments, in order to increase the time to peak and reduce the height of the flood wave downstream (Environment Agency, 2010). This may involve altering multiple elements of a catchment water balance, by promoting interception, infiltration and groundwater storage, enhancing water losses through evapotranspiration, lengthening hydrological pathways and increasing flow resistance. In terms of scale, NFM measures are typically evaluated at the catchment scale, consistent with concepts of whole-system planning (Figure 2.4a). However, specific actions may be more local, depending for example on catchment size, levels of stakeholder acceptance and governance arrangements. Figure 2.4b seeks to show, at least in a qualitative way, the relative difference in the invested capital and net benefit of different flood control strategies, illustrating that costs are typically highest in relation to hard-engineering infrastructure protection. NFM schemes, and more systemically EbA, use the regulating services provided by natural systems, in terms of flow regulation and flood control, but can also realise significantly greater co-benefits (e.g. for biodiversity, landscape amenity, water quality). Hence the benefit-to-cost ratio is potentially much more favourable for these schemes, as would be represented in a total economic evaluation, although this is rarely accounted for in conventional assessments. On the other hand, while engineering schemes provide increased flood protection from the day of completion, NFM schemes generally involve a lag-time to establish. NFM performance also tends to be less certain, because comparable interventions on different hillslope, channel, wetland or floodplain features can produce complex and dynamic responses and divergent outcomes at the catchment scale, as measured for example by runoff and sediment production (Chorley *et al.*, 1985; Schumm, 1979; SEPA, 2012).

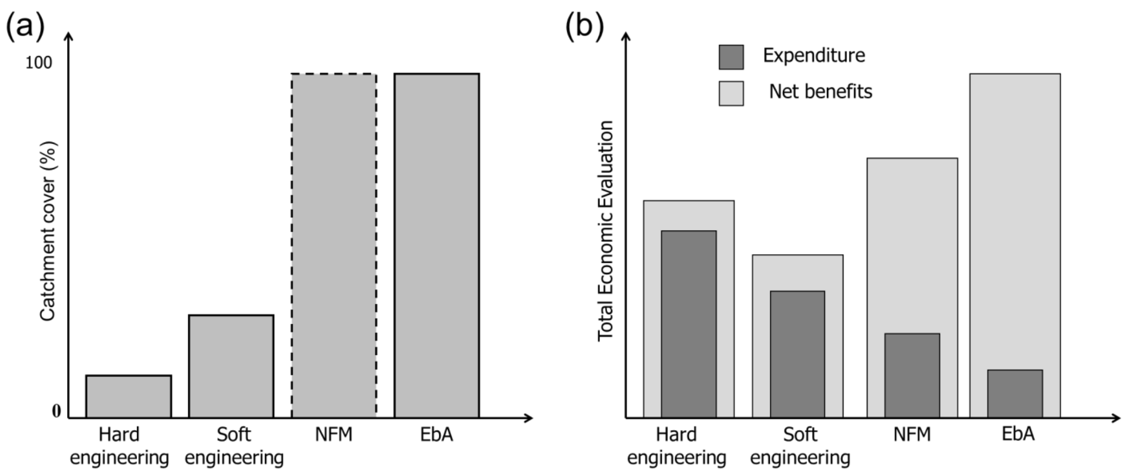

Figure 2.4. The relationship between different approaches for flood risk management: (a) size on which they are being implemented, (b) the financial means engaged in the implementation (Iacob *et al.*, 2014)

The Flood Risk Management (Scotland) Act 2009 is placing a premium on these measures wherever possible, for all statutory bodies. This has already led to a number of initiatives aimed at assessing and promoting the implementation of NFM options in Scotland, including the formation of a NFM group under the Scottish Advisory and Implementation Forum for Flooding (SAIFF), NFM stakeholder workshops and demonstration projects (e.g. Eddlestone).

Several reviews of NFM options have been published since 2004 (Blanc *et al.*, 2012; Environment Agency, 2010; O'Connell *et al.*, 2004; Parrott *et al.*, 2009; Price *et al.*, 2011)**.** Most studies show an overall benefit for flood risk based on the implementation of multiple small scale land management options. However, the need for upscaling is widely acknowledged (Parrott *et al.*, 2009). NFM measures may provide little benefit for large events at a large catchment scale, though they could contribute to flood attenuation by increasing the flood warning times and thus reducing the flood damages.

Following the UK fluvial flooding of 2007, the Pitt Review (2008) emphasized the potential of NFM options as an integrated part of flood protection, encouraging a greater use of natural processes. However, there are still significant uncertainties related to the effectiveness of these natural processes at the catchment scale. A stronger evidence base is needed to identify when the uptake of NFM performance, design and implementation is the best option (Blanc *et al.*, 2012).

2.4.1 River channel restoration

The changes to the River Cherwell have been assessed by Acreman *et al.* (2003) using a hydrological and hydraulic model. The authors reported reductions in the peak discharge by around 10-15% as a result of a combination of river alteration measures, meant to rehabilitate the channel to its natural conditions. By contrast, containing the river in the channel by using channel embankments increased the peaks between 50% and 150%, as it prevented the water spreading onto the floodplain at high flows. The Sinderland Brook study aimed to re-connect the channels to their floodplains, resulting in minimal land use change, but achieving important gains in connectivity, water storage and runoff response (Environment Agency, 2010). Rehabilitation of the river basin by planting, changing riparian and in-stream vegetation and by re-meandering the channelized reaches was investigated by the Steinsel study, using a modelling approach (Liu *et al.*, 2004). The study concluded that following river renaturalisation the peak flows were reduced by up to 14%, and the time to peak was delayed by up to two hours.

2.4.2 Retention ponds

The study of Verstraeten & Poesen (1999) assessed the effectiveness of retention ponds in Belgium. The authors noted that the floods could be reduced, making them acceptable for the drainage system; however, after five years their efficiency would be limited because of infilling with sediments and other materials. The efficiency of retention ponds for flood attenuation was confirmed by Evrard *et al.* (2008) in another Belgian study that recorded a decrease of the peak discharge and increased time lag even for extreme rainfall events (i.e. 150 years return period).

A study in Belford demonstrated the capacity of retention ponds to reduce the flood peaks as part of a system of runoff attenuation measures (Wilkinson *et al.*, 2010).

Niehoff *et al.* (2002) conducted a modelling study to test whether setting 10% land aside (target under the European Union Agenda from 2000) could contribute to reducing the runoff response. The study parameterized the land as having low permeability and tested the runoff response against historic events using a modified version of the WaSiM-ETH model. The results showed only a marginal difference, which might suggest that there is still a need for other interventions to make this type of measure effective.

2.4.3 Drainage/ drain blocking

According to Green (1979) approximately 50% of the productive agricultural land in Scotland is affected by artificial drainage networks. Upland drainage options were implemented historically, to improve land quality for enhanced agricultural, forestry or game bird productivity (Burt, 1995). Drainage in Scotland has thus been implemented primarily to increase the food productivity and access to the land. The aim was to lower the water table to encourage a vegetation cover that was more suitable to livestock grazing (Blanc *et al.*, 2012) (see Figure 2.5). Emerging environmental awareness has shifted the support for these activities, as they came to be perceived by the public as damaging and competing with other environmental values (Smedema, 2011). Some land drains have been maintained, although many became blocked (O'Connell *et al.*, 2007).

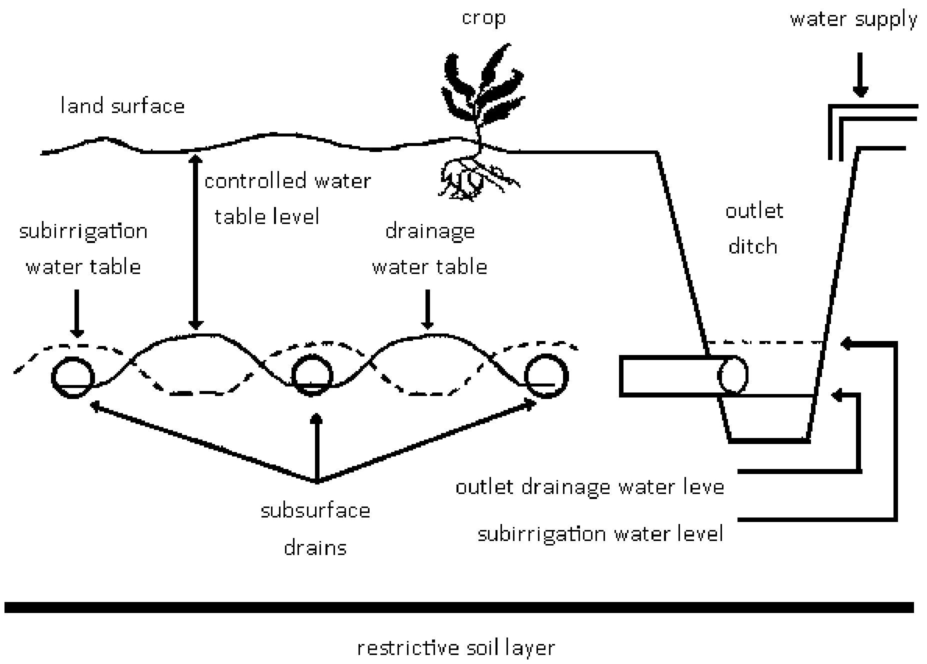

Figure 2.5. Schematic of drainage management systems (FAO, 1997)

Drainage is documented as having significant adverse impact in terms of runoff response. A comprehensive study by Robinson (1990) demonstrated that drainage is very complex and that there is no clear answer as to whether drained land in a catchment contributes to reducing the flooding issue, or contributes to generating higher flood peaks. Field drainage and associated subsoil treatments can increase or decrease peak flows and the time to peak by as much as two to three times either way, depending on the soil type and wetness regime. Robertson *et al.* (1968) and Robinson *et al.* (1998) documented reductions in the 'time to flood peak' parameter for the Blacklaw Moss and Coalburn studies, while Leeks & Roberts (1987) recorded a much peakier runoff response for the Llanbrynmair, following land drainage.

A few studies have assessed the effectiveness of drainage by varying the drainage density parameters in hydrological models. Krause & Bronstert (2007) investigated the impact of coarsening the drainage network using WaSiM-ETH model for a German catchment. The authors assumed a reduction of the river length and noted drier conditions in the central floodplain following the removal of the artificial ditches, whereas non-artificial drainage areas drained the floodplain less effectively in the winter. In the summer the coarsening of the drainage network led to a wetting of the soils due to less groundwater loss. Another study by Wiskow & Ploeg (2003) tested the optimum drain spacing for runoff control i.e. the soil between the drains is water saturated when the recharge stops but no surface runoff is generated. The study varied the drain spacing in a water table model and noted that by allowing water saturation through a coarsening of the drainage system, the runoff control could be improved during periods with elevated recharge.

2.4.4 Afforestation

Forest expansion increased steadily in Scotland from the 1930s onwards, peaking in the 1970s mainly with non-native species (Figure 2.6). Increased concern for the effect of plantation on biodiversity, water quality and landscape was marked by a shift in governmental policies from the 1990s, towards the delivery of multiple benefits and not only the timber yield (Nisbet *et al.*, 2011).

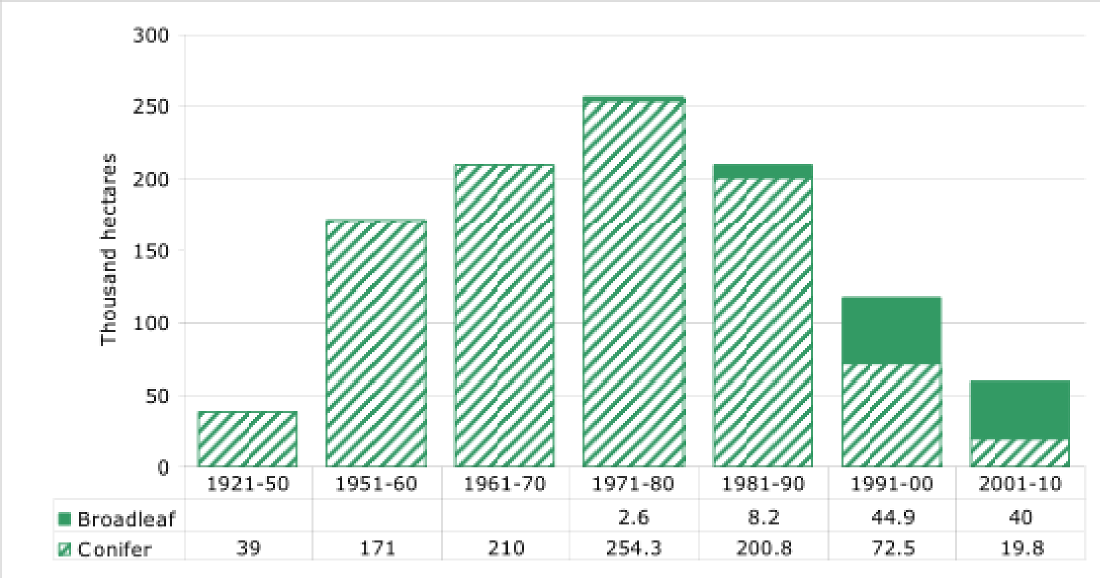

Figure 2.6. Forest expansion since 1921 for Scotland (WEAG, 2012)

The Scottish Government's target for woodland expansion is of 100,000 ha in the next 10 years, which if continued to 2050 would represent almost 50% less than the initial target of 25% woodland cover (Forestry Commission, 2009). This target rate of 10,000 ha/yr represents a major increase from the 3,000 ha per year planted in the 2007-2010 period. The spatial location of new woodland is unrestricted, but the Land Use Strategy states that prime land and peatland should be preserved for food-security purposes and for carbon mitigation (The Scottish Government, 2011). A study by Castellazzi *et al.* (2012) looked at the potential for afforestation across Scotland by defining biophysical constraints as the limitations posed by land use (i.e. water, rocks, montane habitats, urban) and soil information (i.e. alpine and lithosols), with a further consideration of governmental policies on the protection of peatland and prime land by 2050s. The study showed that the potential for woodland expansion is unevenly distributed across Scotland, and catchments with a high potential may be subject to competing demands for the same land.

The capacity of afforestation measures to reduce the flood risk has been demonstrated in a large number of studies. Increasing the coverage of 'forests and woodland' in upstream areas was convincingly shown to reduce downstream flood peaks and base-flows in the Polo, Iller and Parrett catchments (Francés *et al.*, 2008; Park *et al.*, 2006). A study by Wheater *et al.* (2010) reported a reduction of up to 60% of the peak flows for the full afforestation of a 4 km^2 sub-catchment in Pontbren. The Plynlimon study found in general that water yields would be reduced by 1.5-2% for every 10% of additional woodland expansion in the upland catchment, for mature coniferous forest (Calder & Newson, 1979). In the lowlands the interception losses had a larger impact, as the link between the rainfall and evapotranspiration rate and water yield is stronger (Forestry Commission, 2005).

2.4.5 Riparian woodland and woody debris

High flows can be slowed down using riparian woodland, as it reduces the flow velocity, thus contributing to decreased flood risk. A modelling study of the Pickering Beck by Odoni *et al.* (2010) assumed riparian woodland 30 m each side of the channel, and debris dams at a spacing of 7-10 times the channel width along the length of the river. The Manning coefficient was manipulated to reflect the change in hydraulic roughness, and different configurations were tested against two large events. The results show a reduction of 8 to 10% of the peak flows (based on desynchronizing the flows) and a delay in time to peak of 60 minutes. Another study undertaken by Forest Research, Forestry Commission Wales and Interreg IIIC (2007) in the River Fenni catchment used a hydraulic modelling approach to test the impact of large woody debris. The simulation results suggested that dams would have an insignificant impact on the height of the flood peak, but the time to peak could be delayed on average by 2-3 minutes for each dam. The study indicated that the establishment of large woody debris has a greater impact (i.e. increasing travel times) for small events compared to large events.

2.4.6 Floodplain woodland

Floodplain woodlands can contribute to reducing the flood risk, with trunks and other woody structures acting as a physical barrier for runoff, slowing the flow velocity. Research into how floodplain woodland can be used as a flood attenuation option has increased in the last ten years, and is based primarily on modelling studies (Price *et al.*, 2011). Modelling work by Thomas & Nisbet (2006) on the River Cary showed a decrease in flow velocity of 50% and an increase in the water level where new woodland was created, of up to 270 mm. The study changed the Manning coefficient of the floodplain, to reflect the presence of the trees, and the results were assessed for a 1 in 100 year flood event. Another modelling study by Nisbet & Thomas (2008) noted a delayed time to peak of 55 minutes and a reduction in the peak flow of 1-2%, as a result of desynchronized headwaters in the River Laver catchment. The modelling outputs suggest that floodplain woodland could have a significant impact, if several floodplain woodlands are established along the main river channel or on the tributaries. However, the study raised the issue of synchronizing tributaries that were previously desynchronized, potentially exacerbating flooding issues in the catchment, and on this basis recommended the evaluation of all tributaries to see where floodplain woodland would bring the most benefit for flood peak reductions.

2.5 Ecosystem based Adaptation

The EbA approach builds on the Convention on Biological Diversity (1994) definition 'The ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way' (see Figure 2.7). As an approach it includes 'soft' and 'hard' responses in the form of targeted ecosystem conservation, management and restoration actions (Jones *et al.*, 2012). The EbA framework integrates the sustainable use of biodiversity and ecosystem services, with climate change adaptation strategies, both in developed and developing countries (Munang *et al.*, 2013). The EbA framework is guiding the strategies of the United Nations Environment Programme (UNEP) in addressing climate change impacts and helping vulnerable communities increase their resilience.

Naumann *et al.* (2011) reviewed a range of ecosystem based projects used for climate change adaptation in Europe. The review included studies that used an ecosystem services approach, though the term of EbA was not consistent or formally recognized. Comparing between engineered approaches and EbA, the study noted that in economic terms EbA options are not expected to be more expensive than the engineered measures, but they provide a wider range of benefits resulting in a positive cost-benefit ratio. Another review by Doswald & Osti (2012) compiled 101 case studies of EbA for achieving mitigation and adaptation. The authors noted that many studies, particularly for water management, have been labelled as 'disaster risk reduction' or 'landscape management initiatives' meaning that the overall number of EbA projects may be more numerous than initially thought. Climate projections are used frequently in studies using EbA approaches, to ensure that the results are useful in the long term. The study highlighted that the barriers for implementing EbA approaches were lack of funding, community support and required land conversion.

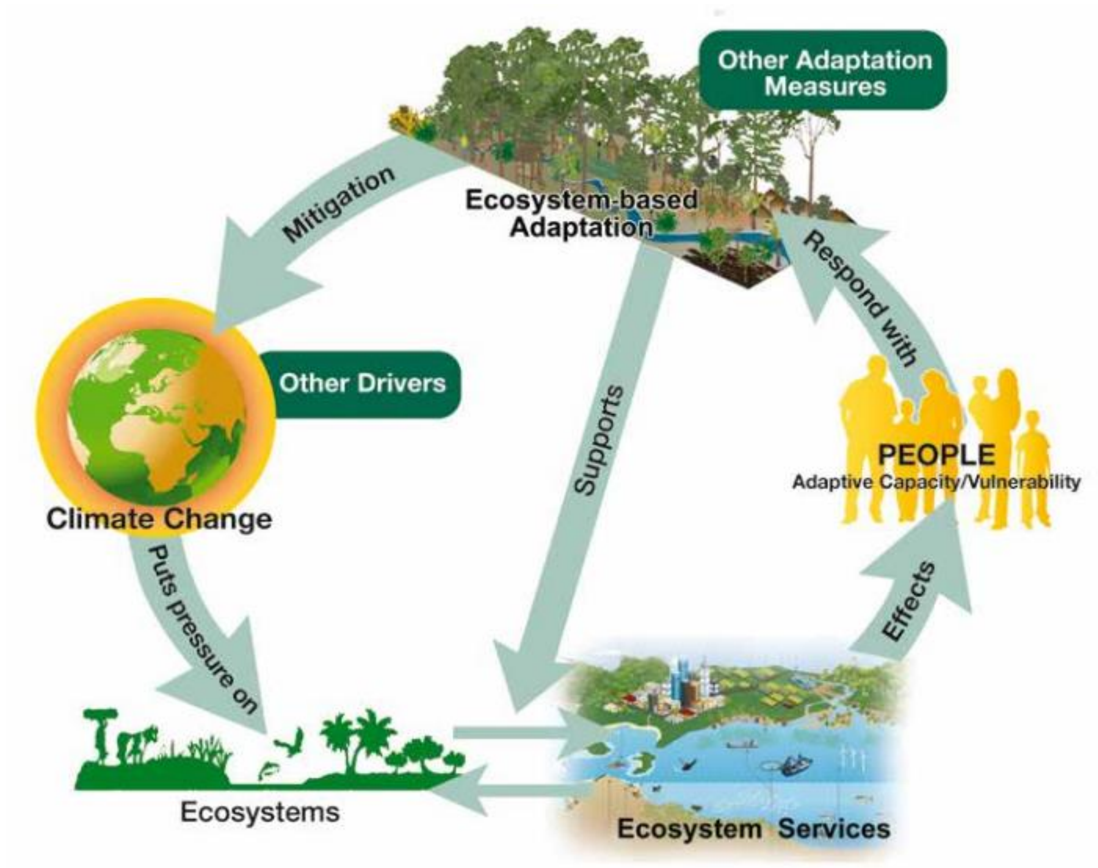

Figure 2.7. Conceptual framework for EbA (Mensah *et al.*, 2012)

The term ecosystem service is not new, having been used and with its values debated for more than 30 years (Haines-Young & Potschin, 2009). However, with the publication of the Millennium Ecosystem Assessment (MA), the significance of the concept has gained momentum. The MA used ecosystem services as a means to evaluate the state of ecosystems worldwide and the impact that changes in their functionality could have for human wellbeing. One of the main findings of the MA was an overall decline of the ecosystem services evaluated (~60%), with consequences for human welfare globally (Fisher *et al.*, 2009).

Building on the MA, the UK National Ecosystem Assessment (UK NEA) was the first systematic assessment of goods and services provided by natural resources underpinning the UK economy (NEA, 2011). The UK NEA showed a similar trend to the MA, with many services being degraded and/or currently declining, whilst the pressure posed by an increased population and climate change is increasing.

In Scotland the principles of the Ecosystem approach and ecosystem services have been included in major areas of legislation, such as the Scottish Forestry Strategy, the

Scottish Biodiversity Strategy, the National Planning Framework and the Scottish Land Use Act. A focus on the delivery of multiple benefits is encouraged through local strategies and plans. Decision makers need to identify areas where there is potential for achieving multiple benefits, and consider how a change in land use will impact on the delivery of ecosystem services.

2.6 Hydrological modelling

To develop sufficiently representative descriptions of past catchment behaviour and assess the impacts of alternative land management options, complex modelling of environmental issues is needed (Choi & Deal, 2008). Hydrological models are being used to understand the change in these systems, with adequate representation of the main hydrological processes. In the last twenty years significant research has been focused on the application of hydrological models to assess the change in hydrological behaviour of catchments, from global scale (Barnett *et al.*, 2005) to single basins (Christensen & Lettenmaier, 2007; Hundecha & Bárdossy, 2004; Singh & Bengtsson, 2005). Modelling tools can be divided into an empirical black box, conceptual lumped models, and the distributed physically-based models (Beven, 2012). A significant number of modelling studies are using empirical black box and lumped conceptual models because of their simplicity, and the low number of parameters that need to be calibrated. However, whilst these may be useful in understanding underlying concepts, they are less reliable in decision making as they simplify the main processes and lack spatial detail. There is therefore a shift towards more complex nested models that allow for the representation of topography, vegetation, land use and soil characteristics, and this is useful for more detailed investigation.

Spatially distributed models are valuable tools for assessing change in environmental system and hydrological cycle components (Viviroli *et al.*, 2009). Distributed modelling approaches have been described as preferred options in providing an accurate description of the hydrological impacts of land use change, as their parameterization considers a physical interpretation of the input (Choi & Deal, 2008). Moreover, their structure allows for the inclusion of spatial variability, and this is particularly important for answering questions that address location-specific questions.

Modelling tools can help improve our understanding of feedbacks and lags, manage uncertainty and improve decision-making by allowing the exploration of management options and possible futures (Choi & Deal, 2008). Most studies use a top down approach for land use or climate change investigation (Wilby & Dessai, 2010), which means that the information is flowing from the climate and hydrological models to assess impacts and then this is used to evaluate adaptation response.

Although a significant number of modelling studies have investigated flooding issues (Cameron *et al.*, 2000; Lamb & Kay, 2004), land use changes (Fohrer *et al.*, 2005; Niehoff *et al.*, 2002) and climate change (Gädeke *et al.*, 2013), an integrated approach which links hydrological models for land use option assessment and climate change investigation is far less common. Hurkmans *et al.* (2009) used land use scenarios to test their significance on river discharge in the Rhine basin, using a modified version of the variable infiltration capacity (VIC) semi-distributed model. Hypothetical scenarios included cropland conversion to forest or grassland, in order to investigate the potential of afforestation options for climate change mitigation simulated through to 2030. Results showed an increase in the flood magnitude across the catchment, for the projected land use change, and a decrease for afforestation conversion. The VIC model does not include bare soil evaporation, so in this case the evapotranspiration was greatly underestimated during the winter period. The authors acknowledged the importance of using a physically based model that is able to simulate all important hydrological processes.

Previous studies undertaken to assess the potential impact of land use change on the main hydrological processes have relied on the use of conceptual, semi-distributed or lumped models (Fohrer *et al.*, 2005; Hurkmans *et al.*, 2009) and physically based distributed models (Niehoff *et al.*, 2002; Thanapakpawin *et al.*, 2007; Wijesekara *et al.*, 2014). Fohrer *et al.* (2005) assessed land use change options in a German catchment, to identify sustainable land use options within an agricultural landscape using the IOSWAT GIS software. He identified the need for an appropriate groundwater representation, especially in areas where the underlying aquifer system played an important role in shaping the hydrological regime. Niehoff *et al.* (2002) linked the LUCK modelling kit for land use change with the physically based WaSiM- ETH model, in order to assess land use options in three catchments within the Rhine basin. The authors noted that combining spatially distributed land use scenarios with physically based hydrological models was an appropriate approach for assessing the impact of land use changes on flood generation. Thanapakpawin *et al.* (2007)

investigated three future land use scenarios (crop to forest and forest to crop conversion) using the DHSVM distributed model in the Mae Chaem catchment. The study noted a sensitivity of the hydrological response to changes in land use, primarily as a result of an increased evapotranspiration rate with land conversion. Wijesekara *et al.* (2014) applied the Mike-SHE and MIKE 11, linked with a Cellular Automata, in the Elbow River basin, to investigate four plausible land use change scenarios. The approach used in the study provided a useful assessment of land use change. However, it was computational demanding, and allowed for a resolution of no more than 200 m. Furthermore, it did not include the groundwater component.

Physical based models are appropriate tools to investigate changes in environmental systems. However, it must be remembered that climatic and hydrological models are uncertain and they should be used with caution (Beven, 2011; Bronstert *et al.*, 2002). There are four main uncertainty sources in deterministic hydrological modelling: (i) random or systematic errors in the input data (ii) random or systematic errors in the model outputs, (iii) errors in model parameterization and (iv) errors in model structure (Butts *et al.*, 2004). Wagener & Gupta (2005) identified three fundamental ideas linked to parameter non-uniqueness. The equifinality issue is based on the assumption that there is more than one optimum parameter configuration in physically based hydrological models that could describe the processes reasonably well (Beven, 2006). The power issue relates to the poor selective abilities and use of available data sets (Wagener, 2003). The third issue refers to parsimony i.e. high complexity models may be inadequate for the set objectives due to heavy parameterization while simpler models might be better considered (Young & Beven, 1994). Until recently the uncertainties related to hydrological models have received less interest in impact assessments (Bastola *et al.*, 2011). Several methods have been developed to identify and analyze the uncertainty in hydrological models, more notably the Generalised Likelihood Uncertainty Estimation (GLUE) method centred around the issue of equifinality (Beven & Binley, 1992), this being more suitable for low parameter number models rather due to its computation demands (Stedinger *et al.*, 2008). Hydrological modelling uncertainties often become insignificant when compared to the uncertainties in the climate predictions (Bastola *et al.*, 2011, Gädeke *et al.*, 2013). Notwithstanding the limitation of the modelling approach for climate change assessments, models are still the only feasible approach to quantify the magnitude of the likely impacts of climate change in the future (Bronstert, 2004).

2.7 Meta-analysis

Twenty-five study catchments were compiled for this analysis, drawn from the review in Scotland of Price *et al.* (2011) and other examples from the wider academic literature (see Appendix A). Most of the study cases are based in the UK, other studies being located in mainland Europe and New Zealand. Consistent with Price *et al.* (2011) four categories of NFM schemes were recognised: (a) (re)establishment of forests and woodland; (b) drainage and drain blocking; (c) wetlands and floodplains restoration; (d) combined measures. The case-study catchments differed greatly in size, spanning four orders of magnitude from 10,000 km^2 to under 1 km^2. Two alternative methods were used across the studies to assess the effectiveness of different NFM proposals: (i) hydrologic and hydraulic modelling exercises to assess flood attenuation potential and (ii) direct monitoring. The variation in scale and lack of consistency in assessment methods present challenges when evaluating the performance of different NFM measures, but these differences do not substantially affect the qualitative ESS analysis undertaken here. The main discussion points are included below; refer to Appendix A for the full analysis results.

In a stationary climate, NFM measures are generally ascribed greater uncertainty as compared with traditional engineering approaches to flood control. Under changing climate conditions such distinctions become blurred. Traditional measures typically focus on water level control in relation to the protection of specific assets, but less attention has been given to flow generation and downstream routing dynamics. The few reliable instrumented catchment studies available span a range of hydroclimatic, landscape and local geomorphological controls, which makes up-scaling from the specific to the general highly challenging. Consequently extrapolating to new situations is a major source of uncertainty in applying NFM.

In addition, the impact of an increased percentage of tree cover is not limited just to the afforested zone. Particularly for riparian woodland the interactions between terrestrial and aquatic ecosystems will lead to alterations of nutrient inputs, changes in micro-climate and contribution of organic matter to the stream and floodplain, and retention of inputs (Gregory *et al.*, 1991). The change may therefore provide benefits such as ‘Climate regulation’ and ‘Biodiversity’ outside the afforested area.

To date the ecosystem service-type assessment has not explicitly considered the significance of a non-stationary climate. However, it is acknowledged that climate change, expressed in terms of systemic trends (e.g. warmer/wetter winters, hotter/drier summers, increased variability and changing magnitude/frequency of events) will also play out in relation to runoff and water quality effects (reflecting altered biogeochemical processes) and land management choices driven by the rapidly developing policy situation.

Moving forward, the selection of NFM strategies should consider both local catchment and wider exposure to climate changes, situating NFM as a central component of EbA (Colls *et al.*, 2009; Jones *et al.*, 2012; Perez *et al.*, 2010). For example, afforestation measures are not recommended in areas where drier summers are projected to occur, as trees directly impact on the water yield and may exacerbate existing drought problems (Ray, 2008). Ensuring the climate-readiness of NFM options requires context specific information, taking into account climate change predictions and further acknowledging how different choices will play out under alternative socio-economic scenarios (Brown *et al.*, 2008; Dunn *et al.*, 2012).

The performance of afforestation measures in reducing the flood peak depends on several factors, notably the previous type of land use. Runoff reductions are likely to be larger and more sustained for afforestation from grassland, compared with afforested shrubland (Farley *et al.*, 2005). Other studies report a higher infiltration rate (up to 60 times more) for young native woodland shelter-belts compared to grazed pasture (Bird *et al.*, 2003; Eldridge & Freudenberger, 2005). The performance is also dependent on the tree species selection (Farley *et al.*, 2005). Species composition and planting style also influence biodiversity gains, with the greatest benefits associated with diverse land use schemes that provide mixed habitats (depending on patch sizes, composition and connectivity). Scale is another fundamental challenge to the assessment process and the examples here span four orders of magnitude within the same NFM category. Theoretically, a larger catchment area has the potential to achieve greater benefits in relation to nationally significant issues such as biodiversity and food production (Hein *et al.*, 2006).

A key point to be emphasised is the evolutionary nature of NFM measures and the lag times in relation to consequent effect on runoff response, which should therefore be considered in NFM planning. This relationship is itself dynamic and susceptible to change over time. Similarly, the relationship between the NFM measure and the co-benefits for ESS is dynamic, and there are often significant time lags to be considered, particularly for the other regulating services in addition to flow regulation (e.g. carbon sequestration, water quality). For example as forest systems mature they have an increasingly strong effect on the environment around them, and their benefit for some of the ecosystem services will increase with time, as is the case for carbon storage (Andréassian, 2004). Farley *et al.* (2005) noted that streamflow response to afforestation is anticipated to be very rapid (within 5 years of planting) with maximum runoff reductions achieved between 15 and 20 years after planting. This was investigated across a wide range of climatic conditions mostly for pine and eucalyptus afforestation. A similar response was recorded by Scott & Lesch, (1997) for South Africa's Mokobulaan catchment. Completely afforesting the catchment with eucalypts was noted to decrease significantly the stream flow after three years of planting, stopping it all together after nine years. The same afforestation with pine trees produced a significant decrease in the fourth year and dried-up the stream completely after 12 years.

The case-studies reviewed indicate overwhelmingly net positive benefits for ecosystem services, subject to the caveat of unintended consequences (cf. Odoni & Lane, 2010). The analysis highlighted that NFM measures provide at the very least 'low regret' options in relation to climate change adaptation, especially in the long term. The study of ecosystem services is increasingly promoted as a cornerstone of effective environmental management, but there remain many methodological challenges to operationalize the approach, and to fully integrate options analysis into decision-making at both the policy level and at the local level by catchment managers. A systems-based approach, incorporating alternative land management scenarios, offers a framework to explicitly include flow and flood regulation as one of multiple ecosystem services, and thus better situate NFM within the wider context of climate change adaptation in the UK.

2.8 Evidenced based policy making

Relevant research for policy making is key for continuous progress at the policy and science interface (Spray *et al.*, 2009), for land use management and climate change adaptation. The Scottish Environment Protection Agency released a Position Statement concerning the use of NFM options for flood protection in 2012 (SEPA, 2012). The document set out the actions that they will take to translate policy requirements in the Flood Risk Management (Scotland) Act 2009 into practice. There are still significant challenges and uncertainties concerning the scientific evidence base for the efficiency of

NFM options (Spray *et al.*, 2009). More research is needed, centred around priority research questions related to 'the catchment scale effects of NFM techniques' and studies that improve 'the understanding of NFM techniques, their effectiveness and issues on the ground' as identified by SEPA (SEPA, 2012). There is also an interest in studies that show how NFM projects can deliver other environmental benefits e.g. biodiversity, rural development (SEPA, 2012).

The Forestry Commission's target for woodland expansion in Scotland is for 10,000 ha each year over the next 10 years (Forestry Commission, 2009). The program aims to integrate the afforestation targets with other land based measures delivering sustainable land use management. Thus, there is a great emphasis on using 'the right tree at the right place'. Afforestation has been closely linked with the delivery of a climate change mitigation target for gas emissions. Moreover, the reporting on the implementation of the woodland expansion strategy feeds into the Land Use Strategy annual reports. However, whilst evidence exists to show that woodland expansion can be efficient in reducing the flood risk (Nisbet & Thomas, 2006), the flood protection objective is not generally linked with afforestation programs (Nisbet *et al.*, 2011).

After the 1970s farmers could not access any governmental grants for drainage maintenance, and they now have to cover their own costs. Evidence suggests that drains have generally been properly maintained with suitable replacement work being carried out (Defra, 2012b), though some of them may be blocked (O'Connell *et al.*, 2007). Implementing adaptation and mitigation strategies, such as afforestation, can have both positive and negative outcomes for water resources, depending on site specific characteristics. As a result, measures should be adapted case by case in order to optimise the effectiveness of adaptation and mitigation measures together.

Chapter 3. Case study catchment description

3.1 Introduction

Tarland Burn catchment has an area of c. 72 km^2 and is located in Aberdeenshire in North East Scotland (Figure 3.2). Positioned centrally in Deeside, Tarland Catchment has its headwaters in the hills above Tarland village and it flows into the River Dee at Aboyne village. The catchment comprises Tarland Burn and a series of small tributaries such as Howe Burn, Burn of Glaaick, Small Burn and Gellan Burn, which drain the surrounding sub-catchments. There are two villages in Tarland catchment, Tarland with a population of 540 people and Aboyne with a population of approximately 2180 (2006 Census).

3.2 Catchment area: past and present

3.2.1 Past: catchment alterations and cultural value of the site

There is a history of long term unbroken occupancy of the catchment dating back to the prehistoric period more than four thousand years ago (Tarland and Cromar Community, 2014). The fertile land of this area made it an important settlement and farming locality (Figure 3.1). The area is rich in historic and prehistoric sites with many recumbent stone circles, found only in the North East of Scotland. Examples of such artefacts are the Recumbent Stone Circle at Tomnaverie, a souterrain or earth house at Culsh, as well as numerous burial cairns, stone circles, Pictish stones and Bronze Age fortifications (Welfare, 2011). The site is therefore important for its cultural ecosystem services which need to be recognized and included in land management decision making.

Figure 3.1. Tarland catchment

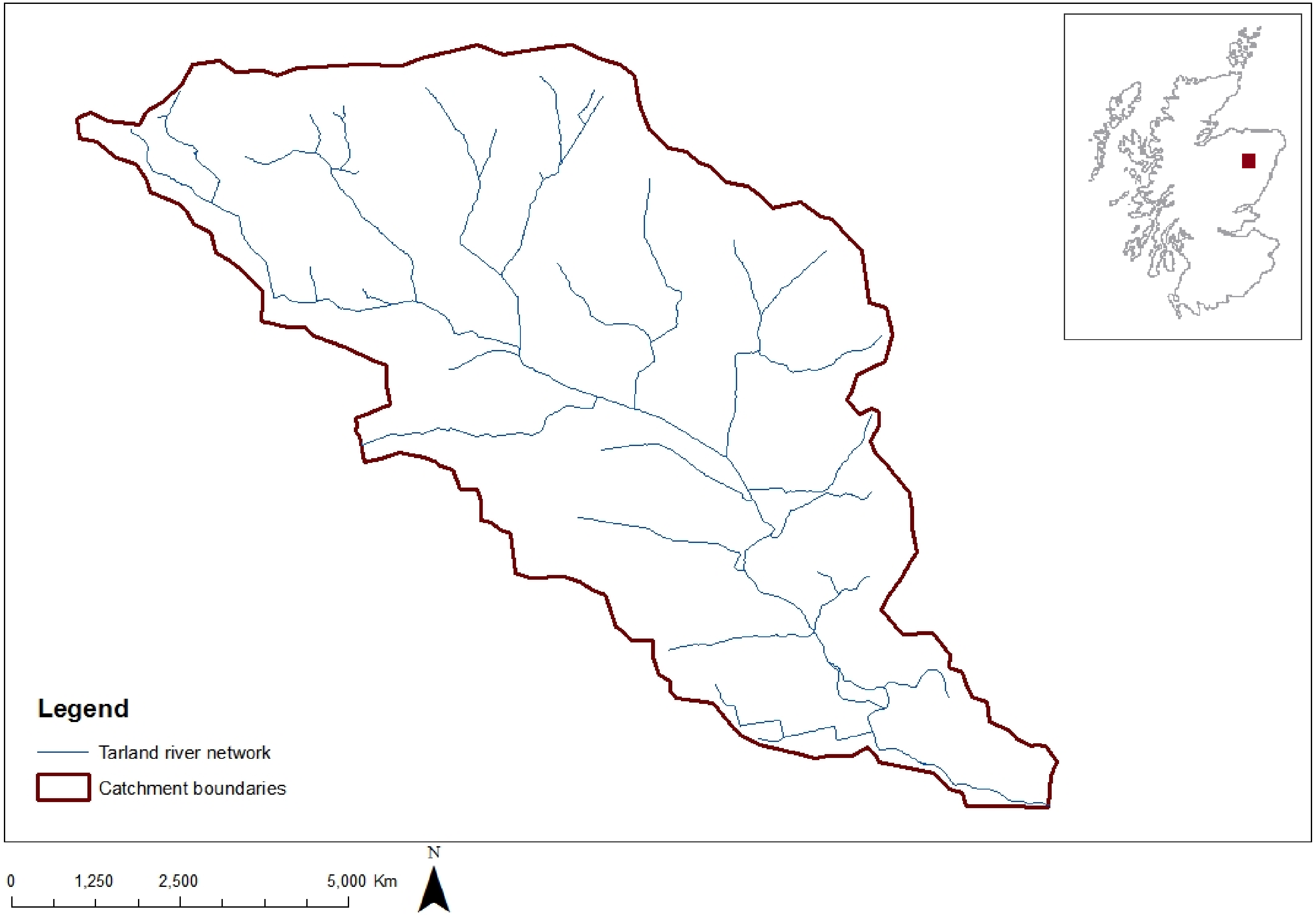

Figure 3.2. Location of Tarland Burn catchment

It is recognized that the catchment of Tarland Burn has undergone many changes in the last two centuries, primarily to improve agricultural potential. However, it is not clear when some of these changes were made, with the best evidence relating to changes in the 19th century, for which historic maps and statistical accounts are available. This includes surveys conducted around the 1820's and 1830's for the Robertson Map and Thomson Map (Figure 3.3), and those for the Ordnance Survey's six inch 1st Series map in late 1860's, as well as statistical accounts from the Parish for Tarland and Migvie, and for the Coull Parishes for the period 1791, 1799 and 1845. The earlier accounts describe Tarland as a plain, with very little water during the summer, though with regular flooding in the winter months and during heavy rainfall events. The later accounts describe 'great improvements' in the area as a result of the increased drainage works and better management of water resources and distribution (McKeen, 2013).

3.2.2 Present

Comparing the Thomson map with today's Ordinance Survey map (Figure 3.4) it can be seen that there was a significant reduction of wetlands, which provide natural flood storage by slowing the response of the runoff during extreme flood events. The former braided section of the river downstream from Tarland village is now heavily channelized. Lochans and small ponds have also been displaced. Significant alterations have been made to the channel between the Aboyne castle and Aboyne, which includes the split of the main burn around the Aboyne castle estate. It can also be seen that the man-made Aboyne Loch has been established, absent in the Thomson map. The Tarland burn was also lengthened where it joins the Dee River, which is now significantly further south than indicated in 1832 (Stutter *et al.*, 2005). There is a mismatch for the main channel downstream from Coull Bridge which may be the result of inaccuracies in the Thompson survey (which are indicative rather than precise) or geo-referencing issues.

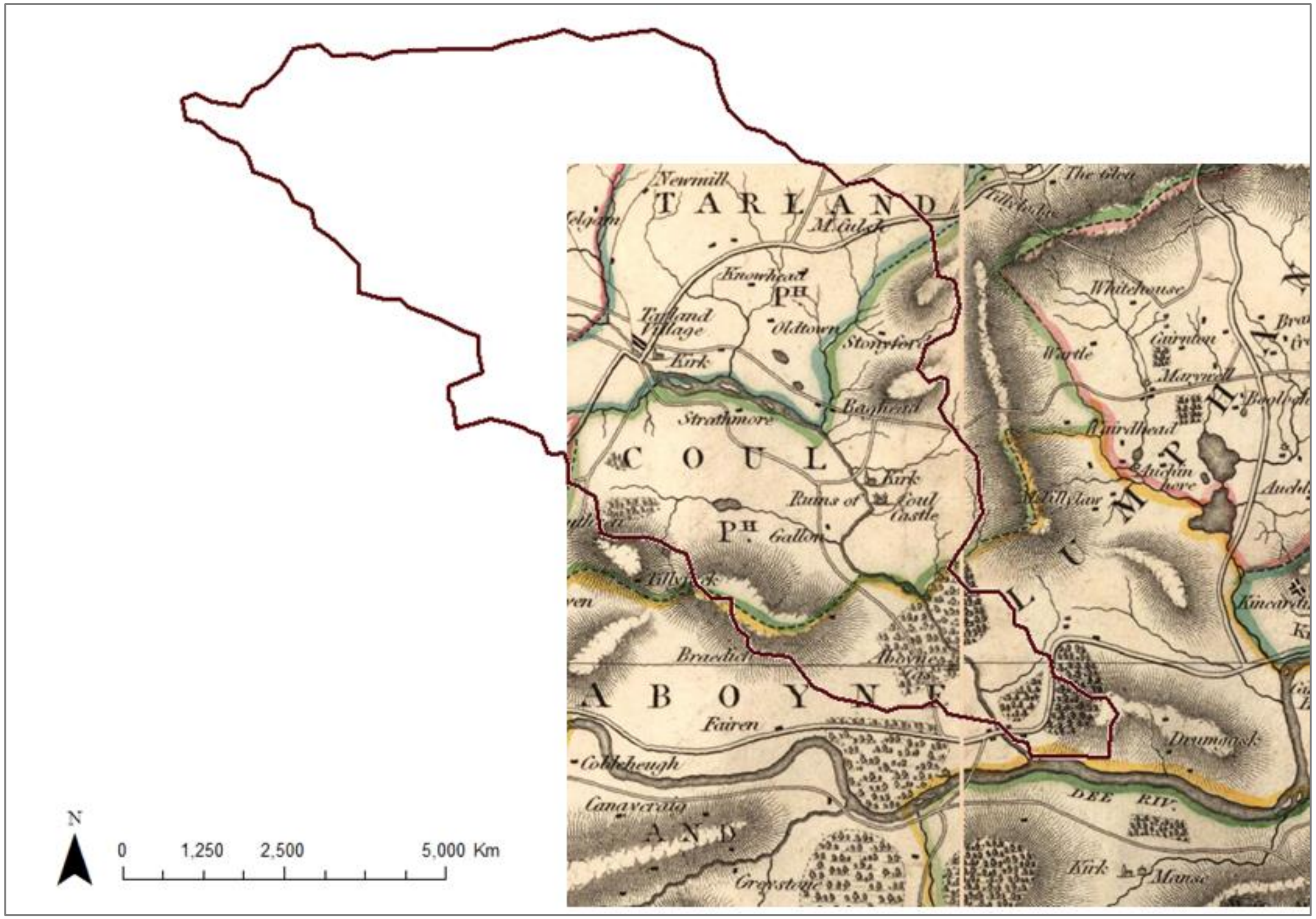

Figure 3.3. Compiled map of the Tarland catchment from sheets of John Thomson, Northern Part of Aberdeen and Banff Shires, Southern Part (1832). Reproduced with the permission of the National Library of Scotland

Note: the maps are 'on a scale so large as to exhibit the features of the county, and places of interest' (Thomas & Williams, 1832)

Figure 3.4.Comparison between the river channel from the Thomson map (1832) and the present OS map

Compared with the Thomson map from 1832 there is also a significant increase of woodland cover. The present cover comprises the mixed pine and birch woodland east and southwest of Balnagowan and south of Aboyne, which existed in 1832, which was extended particularly around Balnagowan hill and west of Mortlich. In the present-day landscape there are a number of commercial forest plantations, but also areas of natural birch woodland (Stutter *et al.*, 2005).

3.3 Topography and geology

3.3.1 Topography

The elevation in Tarland Burn catchment varies between 100 m in the valley bottom and 617 m on the hill top (Figure 3.5). The topography has an impact on the meteorological regime in the catchment and on the type of land cover and land uses. The hills surrounding the catchment receive more rainfall because the air temperature is lower and closer to the condensation point, at which water vapour is converted into water droplets. Moreover, the air masses are pushed upwards over the hills, which add to this effect, whereas with regular westerly winds air masses descend over Aboyne. Therefore, Aboyne is in a rain shadow, with Tarland village experiencing to some extent the same

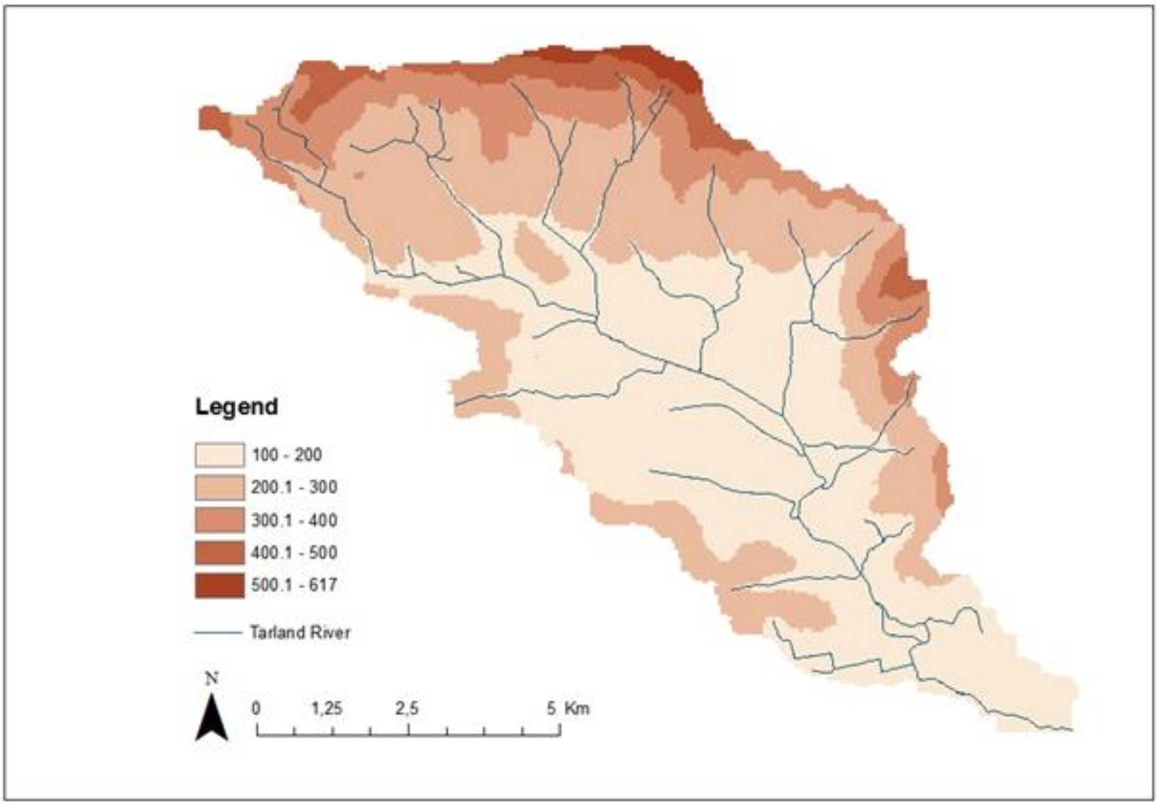

Figure 3.5. Tarland Burn catchment DEM

effect. The topography also determines the speed with which the runoff will reach the river. Rain that falls in uplands will reach the primary river in the watershed faster than for flat or lightly sloping areas.

3.3.2 Geology and aquifer

The Southern Highland Group creates the underlying geology in Tarland catchment (Figure 3.6). The metaphoric rocks of psalmite and pelite are created from sedimentary rocks exposed to igneous intrusion. These igneous intrusions enclose the catchment, having formed approximately 420 million years ago in the late Silurian period. The rocks are comprised of muscovite, quartz and orthoclase minerals, also known as felsic rocks (Sewell & Hutton, 2010). The rocks in Tarland are characterized by low hydrogeological transmisivity in the region of 1 m^2/day. The presence of the fault that runs through Aboyne and the River Dee, can cause increased local fracturing and weathering. The superficial deposits (Figure 3.7) are predominantly a mixture of till with some alluvium on old lake bed and river channel, together with sands and gravel fluvioglacial outwash (McMillan *et al.*, 2004). These superficial deposits are of significant extent and of similar thickness to the rest of the Dee Valley, which makes them highly permeable with a high storage capacity.

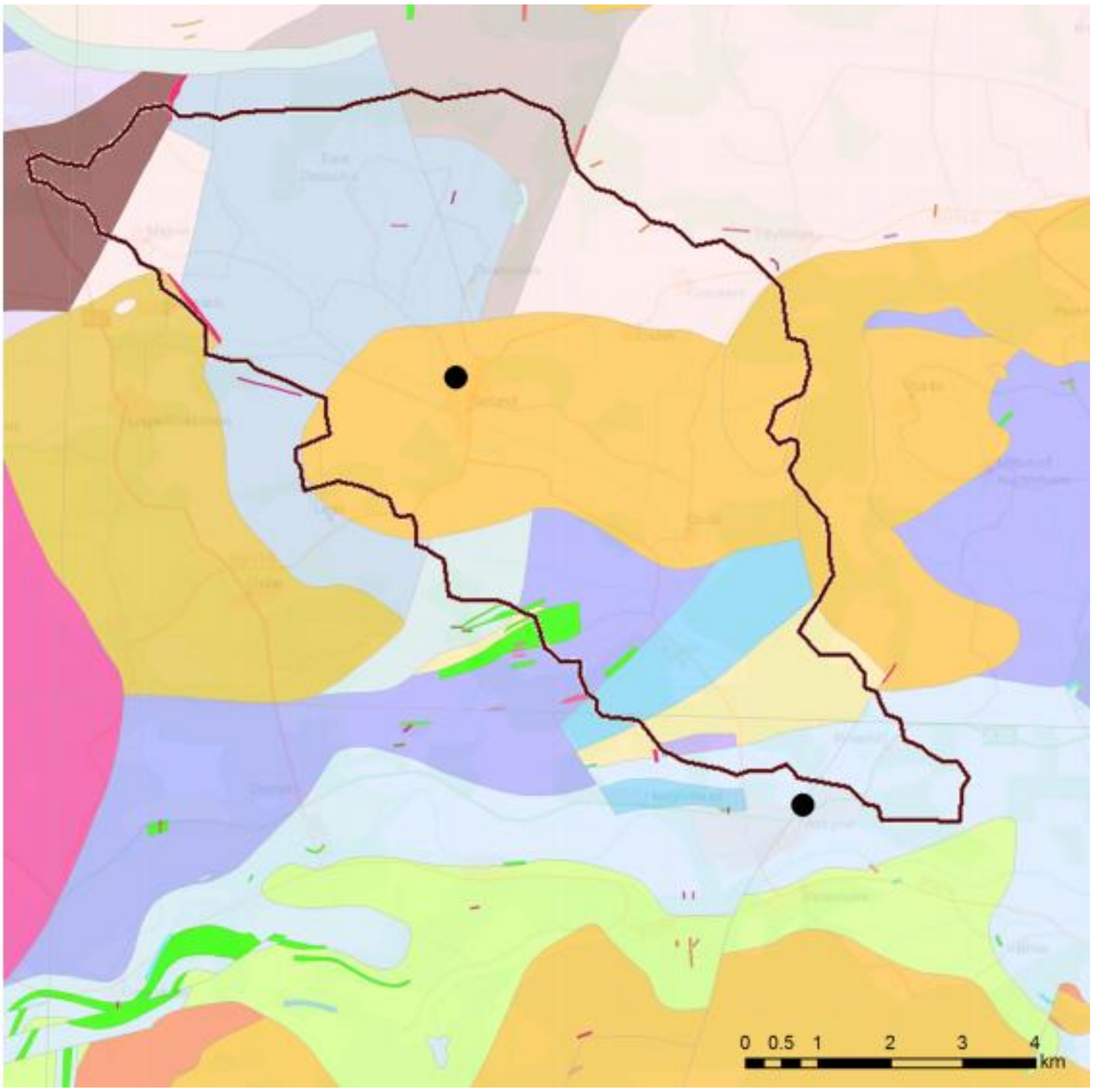

Figure 3.6 Bedrock geology Tarland Burn catchment

Legend

- Morven-Cabrach Pluton—Olivine—Gabbro, Fe-rich
- Deeside Limestone Formation—Calcsilicate Rock
- Queen's Hill Formation—Psammite and Semipelite
- Queen's Hill Formation—Semipelite, Psammite and Pelite
- Deeside Limestone Formation—Psammite and Semipelite
- Deeside Limestone Formation— Metalimestone
- Craigievar Formation—Migmatitic Psammite with Migmatitic Semipelite
- Craigievar formation—Metasedimentary rock
- Tarland intrusion—Norite and Gabbronorite
- Morven-Cabrach Pluton—Serpentinite
- Torphins Intrusion—Tonalite and Quartz—Diorite
- Craigievar Formation—Pelite, Migmatitic
- Queen's Hill Formation—Psammite
- Ballater Pluton—Leucogranite
- North—East Grampian Granitic Suite (Ordovician) - Granite
- North Britain Siluro– Devonian Calc-Alkaline Dyke Suite—Felsite, Porphyritic
- Tarfside Psammite Formation—Quartzite, Psammite and Semipelite
- North Britain Siluro—Devonian Calc-Alkaline Dyke Suite—Microgranite, Porphyritic
- North Britain Siluro—Devonian Calc—Alkaline Dyke Suite—Microdiorite
- Central Scotland Late Carboniferous Tholeitic Dyke Swarm—Quartz—Microgabbro
- Cromar Pluton—Granite
- North Britain Siluro—Devonian Calc—Alkaline Dyke—Pegmatite, Brecciated—Feldspar—Quartz
- Kincardine O'Neil Intrusion—Granodiorite
- Logie Coldstone Intrusion—Tonalite
- Morven—Cabrach Pluton—Norite
- North Britain Siluro—Devonian Calc—Alkaline Dyke—Felsite
- North Britain Siluro—Devonian Calc—Alkaline Dyke Suite—Lamprophyres
- Neoproterozoic—Basic Minor Intrusion Suite—Amphibolite and Hornblende Schist

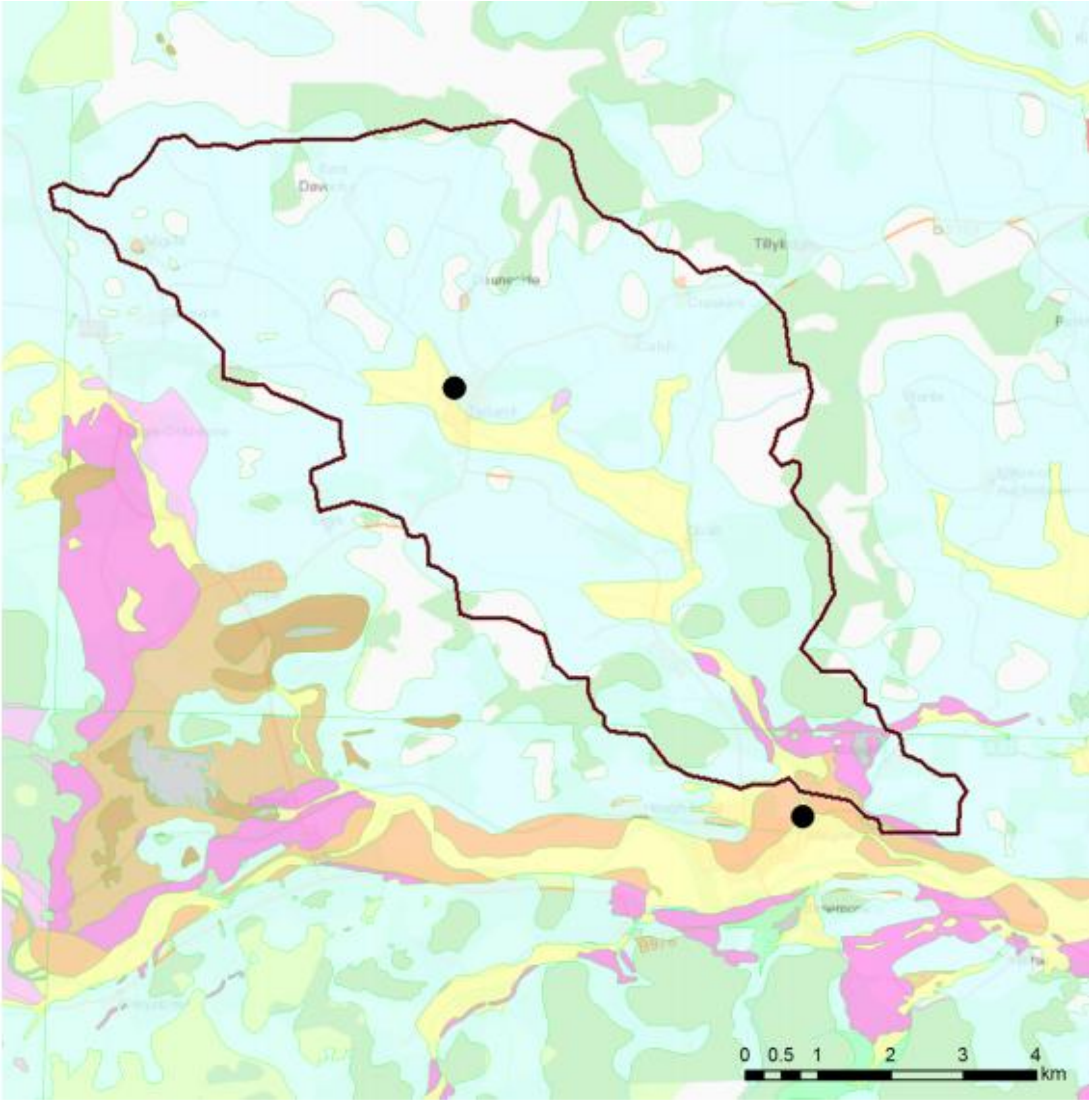

Figure 3.7. Superficial deposits Tarland Burn catchment

Legend

- Glaciofluvial Deposits—Gravel, Sand, Silt and Clay
- Glaciofluvial Sheet Deposits—Gravel, Sand and Silt
- Banchory Till Formation—Diamicton
- Lochton Sand and Gravel Formation—Sand and Gravel
- Hummocky (Moundy) Glacial Deposits—Diamicton, Sand and Gravel
- Alluvium—Clay, Silt, Sand and Gravel
- River Terrace Deposits—Gravel, Sand and Silt
- Lacustrine Deposits—Clay, Silt and Sand
- Peat
- Superficial Theme Not Mapped

3.4 Land use and drainage network

3.4.1 Land use

The land use in the catchment is an amalgam of mixed farming, coniferous plantations and semi-natural habitats (Figure 3.8, Table 3.1). The lower zone of the catchment is predominantly agriculture comprised of arable fields and improved grassland, supporting cattle, sheep, barley and potato, whilst the headwaters of the catchment have steeper slopes and consist of rough grassland, heather moorland (much of it maintained for grouse shooting), and widespread plantation forestry. Compared to the rest of Scotland, Tarland Burn has a larger percentage of arable, grassland and woodland whilst lacking other land use types e.g. bog (Countryside Survey, 2007).

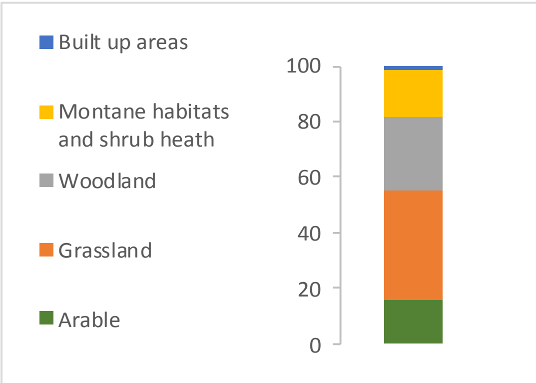

Figure 3.8. Land use distribution in Tarland catchment

Table 3.1. Percentages of land use

Land use	% Tarland	% Scotland
Arable	15.7	6.6
Grassland	39.4	29.6
Woodland	26.4	17
Montane habitats and shrub heath	17.2	12.4
Built up areas	1.1	1.9

The Tarland catchment and three of its tributaries (Burn of Blackmill, Burn of Glaaick, and the Stoneyford Burn) are included in the larger Dee Special Protection Areas under Natura 2000, on the basis of their high environmental value. These areas are internationally important for their populations of Pearl Mussels (*Margatifera margatifera*), Otter (*Lutra lutra*) and Salmon (*Salmo salar*) (The Macaulay Institute for Soil Research, 2008). The areas are also notable for ospreys, the common lizard, adders, bat species and Red Squirrels. Farms in the catchment are predominantly focussed on mixed farming, followed by cattle and sheep raising, and cereal production (Table 3.2).

Table 3.2. Farm types

Robust Farm Types	No holdings	Area (ha)
Cattle and sheep	19	1748
Cereals	6	613
Dairy	1	135
Specialist poultry	1	9
Mixed	11	1983
Other	13	315
Total	51	4802

*Source: The Macaulay Institute for Soil Research, 2009

3.4.2 Drainage network

Surface and subsurface drains in Tarland were set in place as early as the 1840s, the majority of the drainage work being carried out between the surveys conducted for the Thomson and Robertson maps in the 1820s and 1832 respectively, and the survey for the OS six inch 1st Series map in 1869 (Figure 3.9). This is consistent with the Land Drainage Acts (Scotland) in 1833, 1847 and 1861, which allowed loans and grants to land owners in order for them to improve drainage for better agricultural yields. This was facilitated by improvements in agricultural machinery and innovation, including the invention of the hollow-pipe drainage method in the 18th century by Sir Hew Dalrymple (McKeen, 2013). Drainage works were also boosted by the change in leases in the area, which meant that the tenants could rent their land for a period longer than one year. This encouraged tenants to invest more resources in their land, such as improved infrastructure for easier access to markets and suppliers, and land enclosements (Douglas *et al.*, 1923). The Parish Statistical accounts for Tarland, Migvie and Coull parishes, for the period 1791-1799 and 1845, summarize these drainage changes: '*the lands have been inclosed and drained, and many of the recent improvements in the construction of farming implements have been adopted'*. In the Edinburgh Gazette there are entries related to funds which were granted to land owners for drainage work, and to ensure clean water supplies to towns and cities under the Public Health (Scotland) Act 1867 (McKeen, 2013).

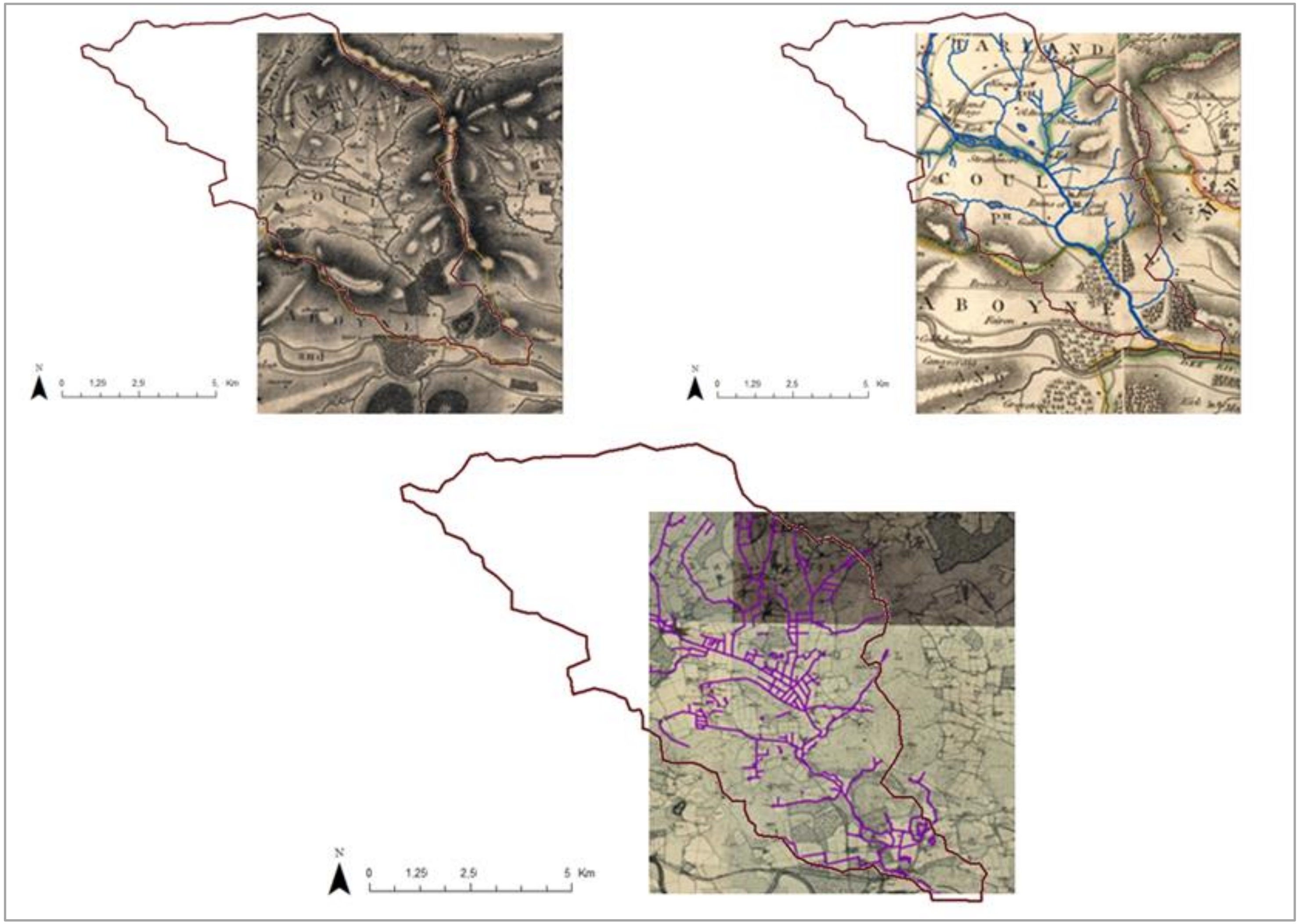

Figure 3.9. Historic maps (a) Robertson Map (1832), Thomson Map (1820), OS 1st Series (1866-1869). Reproduced with permission from the Trustees of the National Library of Scotland.

3.5 Climate and meteorological stations

3.5.1 Local climate

The climate in Tarland Burn catchment is typical for the East of Scotland. The East is characterised by an annual mean maximum temperature of 10.8 °C with the annual mean minimum temperature of 3.8 °C. In Tarland the temperatures range between a mean of 12.2 °C in the summer to a mean of 3.5 °C in the winter (Figure 3.10). The average annual precipitations recorded at Aboyne station is 780 mm, less than the average for the East of Scotland which is 1182.6 mm (cf. Met Office). However the Aboyne station is not able to accurately capture the precipitation for the whole Tarland catchment. Further discussion and data correction analysis undertaken for the current research is provided in section 3.7.1.

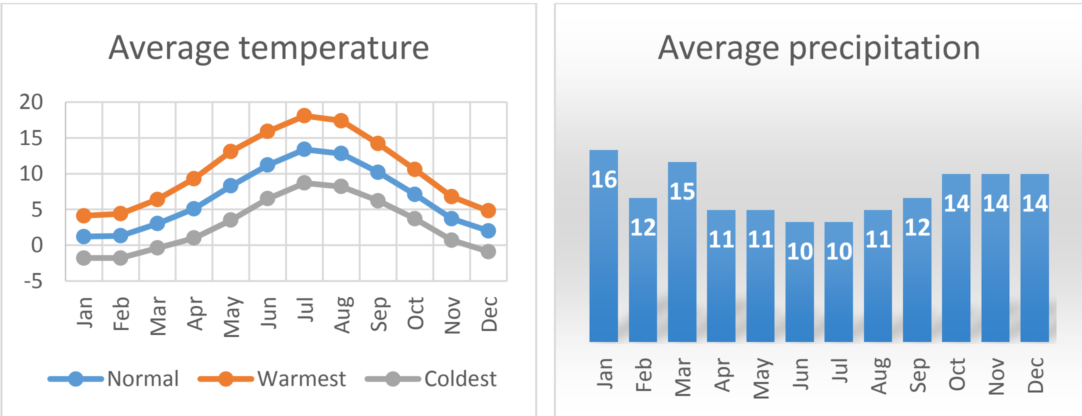

Figure 3.10. Average temperature and average days with precipitation per month in Tarland catchment

Table 3.3 presents the average maximum and minimum daily temperatures per month, and the precipitation for Tarland catchment, based on data from 1961 to 1990. Here, a day with precipitation is considered when the precipitation exceeds a threshold of 1 mm. Tarland catchment has between 50-80 days of sleet and snow falling (annual average 1971-2000) and between 30-50 days of snow lying (annual average 1971-2000, approximated from Barnett *et al.*, 2006b).

Table 3.3. Average temperature and precipitation per month in Tarland catchment

Month	Max. temp (°C)	Min. temp (°C)	Days of air frost (days)	Rainfall (mm)	Days of rainfall >= 1 mm (days)	Monthly mean wind speed at 10m (knots)
Jan	6	-1	16	66.2	12.8	7.5
Feb	6.5	-0.9	15.1	48.5	10.7	7.4
Mar	9	0.6	11.6	53.6	11	7.7
Apr	11.5	2	7.6	56	10	6.4
May	14.6	4.2	3.5	59.1	11.5	5.6
Jun	17.1	7.5	0.2	55.6	10.2	5.5
Jul	19.4	9.4	0	67.9	10.7	5.1
Aug	18.7	8.9	0	60.8	10.7	4.9
Sep	16.2	6.9	0.6	68	9.2	5.6
Oct	12.2	4	4.8	92.7	12.9	6.1
Nov	8.6	1.3	10.1	84.8	12.6	6.1
Dec	5.9	-1.1	16.3	66.9	11.6	6.4
Annual	12.2	3.5	85.9	780	133.7	6.2
Average annual Scotland	10.8	3.8	77.0	1182.6	161.4	-

Source: Met Office for the climate period 1981-2010 at Aboyne station

3.5.2 Meteorological stations

Precipitation data at hourly time steps are available at Aboyne station operated by the UK Met Office. The station is located at 57.076 latitude and -2,839 longitude at an elevation of 140 m. It is an automatic station which has recorded meteorological data since 1989.

3.6 Hydrometric stations

There are four permanent flow gauges in the catchment operated by a number of different organisations (Table 3.4). None of these stations appear in the Environment Agency HiFlows-UK database, which provides the peak flow and level data at a large number of river gauging stations across UK. Possible reasons why these gauges have not have been included could be (i) that their record lengths are too short or (ii) because they are considered unreliable.

Table 3.4. Gauge stations in Tarland catchment

Gauge station	Operated	Location	Type	Data interval	Record length
Aboyne	SEPA	NO (37) 532 987	Rated section	15 minutes	2003 – present
Aboyne	Aberdeenshire Council	NO (37) 529 988	Rated section	15 minutes	2003 – present
Coull Bridge	James Hutton Institute	NJ (38) 510 025	Rated section	Hourly	1999 – present
Tarland village	Aberdeenshire Council	NJ (38) 481 043	Rated section	15 minutes	March 2002 – present

The gauge data at Aboyne (Aberdeenshire) were not available and the rating curve at Tarland village gauge is not considered reliable (pers. comm. Wilkinson, 2013) and so these datasets were excluded from the modelling work. Aboyne station (SEPA) and Coull Bridge stations shown in Figure 3.11 were used for this study, and are further described.

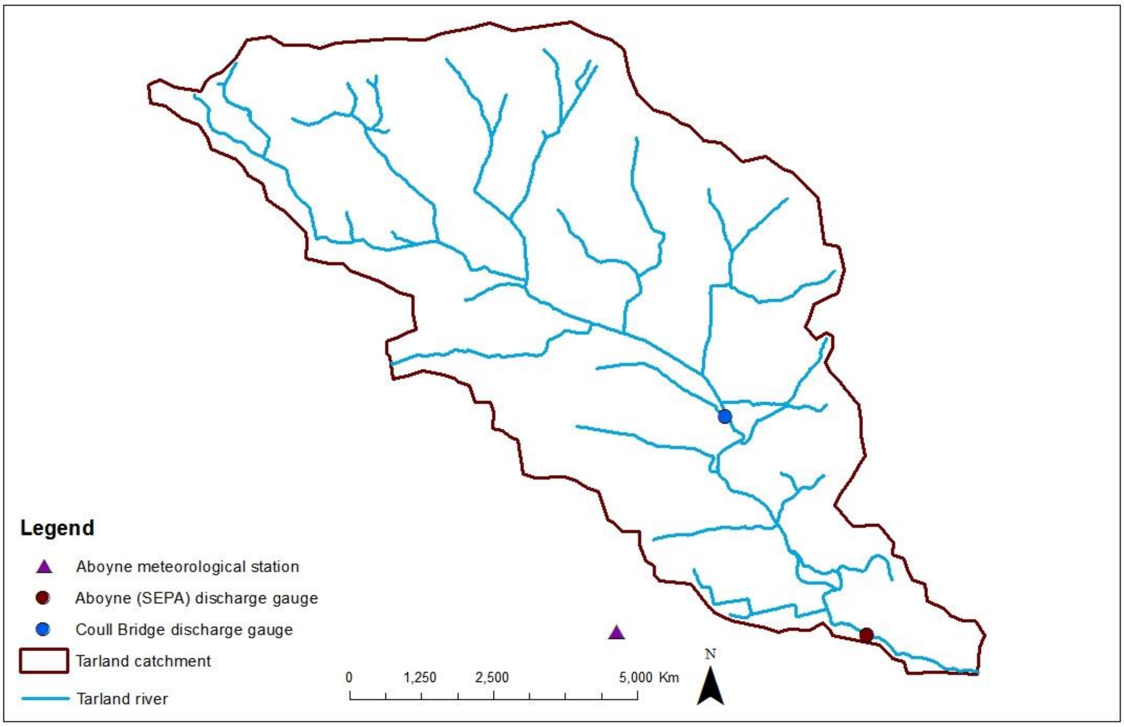

Figure 3.11. Meteorological and discharge stations in the Tarland catchment

3.6.1 Coull Bridge gauge station

The Coull Bridge station is located downstream from Tarland village (see Figure 3.12). The station was established in 1999 as part of the Tarland Catchment Initiative (TCI), to measure basic water depth and water quality parameters such as dissolved oxygen, turbidity and electrical conductivity. The objective of the Initiative was to implement a strategy for the sustainable use of the catchment and to improve the water resources in the catchment.

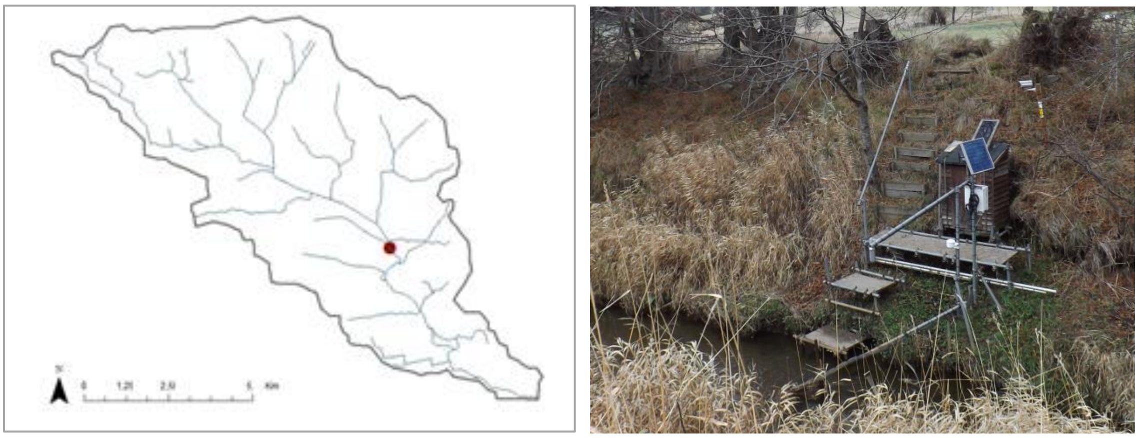

Figure 3.12. Location of Coull Bridge station

The channel at the Coull Bridge gauge is deep, around 4.8 m. Cross-sections at the gauge were not available, but the cross sections upstream and downstream of the gauge are presented in Figure 3.13 based on two surveys of unspecified dates (Sewell & Hutton, 2010). The catchment area at this gauge is approximately 52 km^2 and it is located within the middle reaches of the catchment. The predominant land use in the area surrounding the gauge is agricultural.

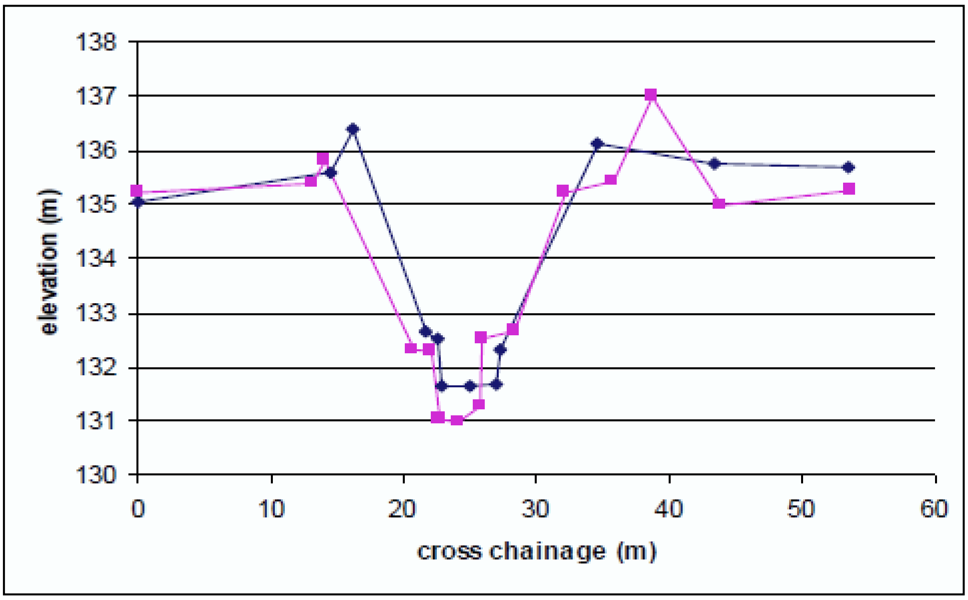

Figure 3.13. Cross section of Coull Bridge station (source: Sewell & Hutton, 2010)

The initial assumption was that the discharge data for Tarland catchment are very well described, characterised and understood. Further investigation showed that the data are much less robust which posed challenges in the calibration and validation phase of the modelling exercise. The rating curve at Coull Bridge station is presented in Figure 3.14. The shift of the rating curve over time is a result of intense channelization work and sedimentation in the burn channel. A limitation of this rating curve is that there were only a few measurements taken between 2005 and 2012. Moreover, most of the measurements are in-channel events, only in 2012 was there one high flow measurement which corresponds to a 1 in 5 year flood (cf. Ghimire, 2013).

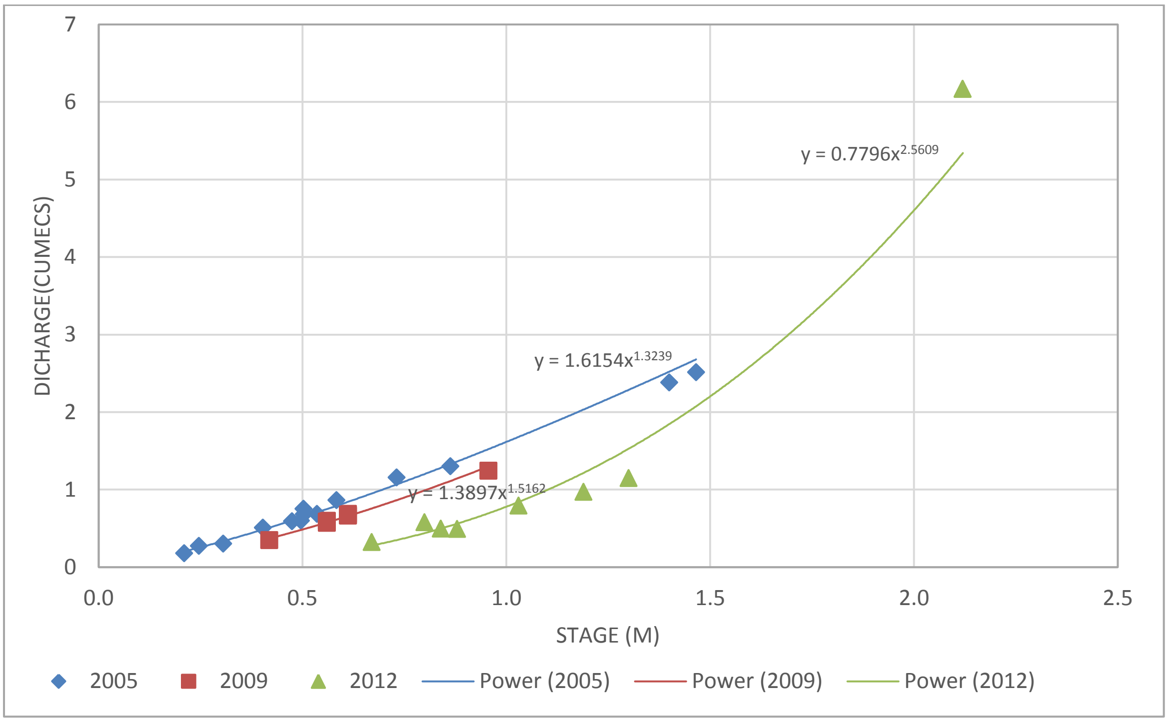

Figure 3.14. Rating curve for Coull Bridge gauge station

3.6.2 Aboyne (SEPA) gauge station

The installation of a flow gauge at Aboyne, managed by SEPA, has been driven by the occurrence of significant flooding events in the area and the high level of interest in the catchment for research. The gauge was installed at the Junipers in 2003 and it is positioned at a flat deck bridge with the gauge board located at the downstream abutment of the deck bridge (Sewell & Hutton, 2010). The catchment area at Aboyne (SEPA) station is approximately 70 km^2 and is situated at 117 m altitude. The channel at this location is engineered with a masonry revetment to either side (as illustrated in Figure 3.15).

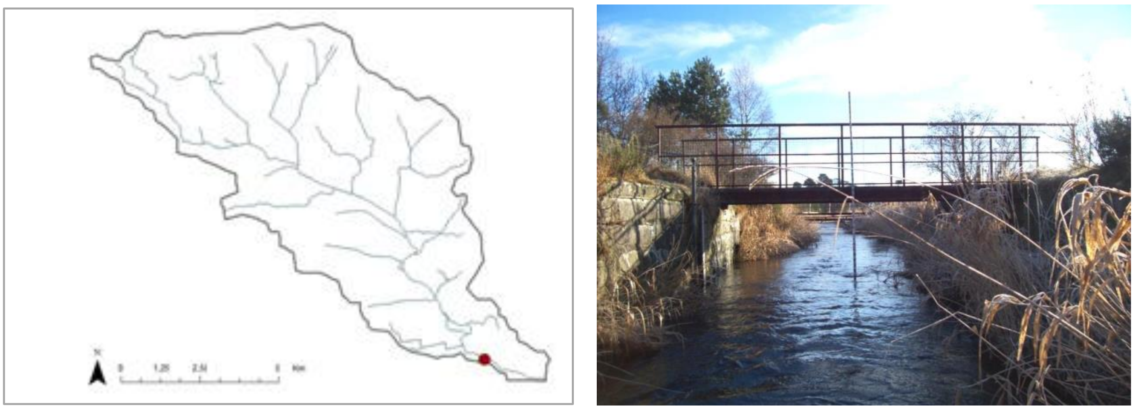

Figure 3.15. Location Aboyne (SEPA) station

The channel depth at the station is around 2.2 m as seen in Figure 3.16. Upstream of the gauge there is a small hydraulic step, this is directly downstream of the large masonry arch bridge, and it is unknown whether the step is a natural feature or manmade (Sewell & Hutton, 2010).

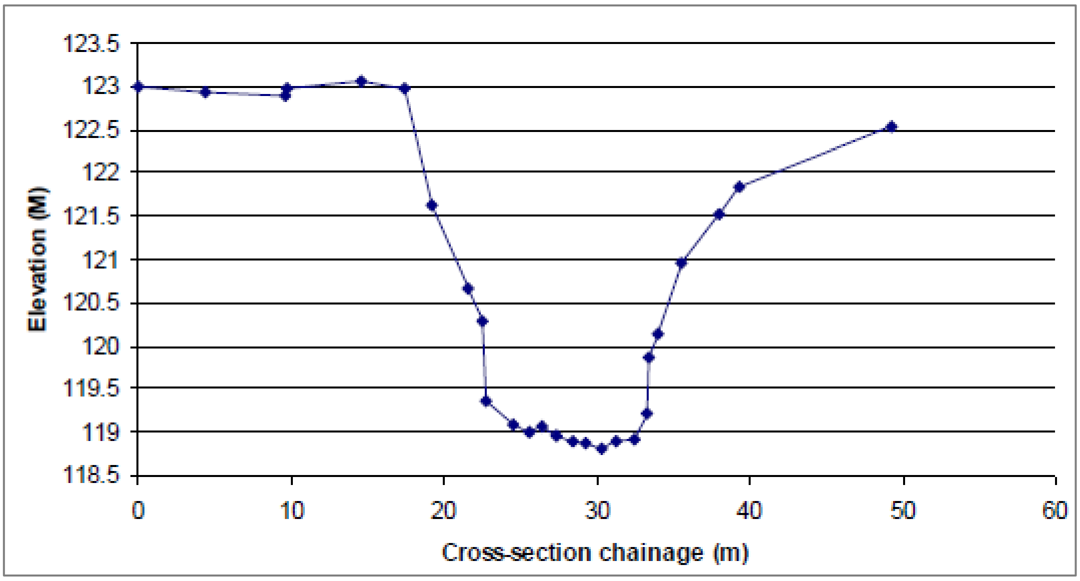

Figure 3.16. Cross-section for Aboyne SEPA station

The rating curve at Aboyne was not available, but there are known issues with the discharge gauging at this site. The site has no cableway and there are difficulties in gauging at higher levels, and weeds might pose an issue for lower flows (pers. comm. Thom, 2015). There are also concerns that when the River Dee has high flood flows there might be some backing up of the Tarland at the Aboyne site location. Moreover the data presents gaps due to standalone level logger malfunctions (pers. comm. Thom, 2015). The rainfall runoff peak estimates were calculated by Sewell & Hutton (2010) based on the Flood Estimation Handbook (FEH) method using the Infoworks software (the FEH method is described in detail in Chapter 4, section 2).

Table 3.5. Design peak flows estimation (Sewell & Hutton, 2010)

Return period	50%	20%	10%	4%	2%	1%	0.50%
Aboyne	7.4	10.2	12.1	14.8	17.1	19.6	22.4

Based on the design peak flow estimates, the flood frequency graph was developed and presented in Figure 3.17.

Figure 3.17. Flood return period levels at Aboyne (SEPA) station

3.7 Data correction

A minimum quality of precipitation and discharge data is crucial for model calibration. Several problems were identified with these two sets of data for Tarland catchment during the model calibration process. A discussion on how these issues have been addressed is provided below.

3.7.1 Precipitation correction

The Aboyne station is located on the southern side of the catchment close to the River Dee. Due to the complex topography of the catchment (see section 3.3.1), the station is unable to accurately represent catchment rainfall variability. The issue of under-representation of rainfall in mountain regions due to complex precipitation gradients and lack of rainfall gauges is widely acknowledged (Johansson & Chen, 2003; Prudhomme & Reed, 1999). Most climate stations are located in valley bottoms with easy access but they record lower precipitations compared to the neighbouring higher altitude areas (Johansson & Chen, 2003). Additional information is therefore needed to account for the influence of topography (Prudhomme & Reed, 1999). Several methods have been proposed, such as statistical relationships that describe the interactions between precipitation, airflow and topography (Johansson & Chen, 2003), geostatistical algorithms that include DEM in rainfall predictions (Goovaerts, 2000), or the FORGES method (Prudhomme & Reed, 1999).

To address the issue of rainfall under-representation in Tarland Burn catchment, the monthly precipitation total at Aboyne has been compared with gridded MetOffice data for Tarland catchment. The gridded Met Office data are based on the archive of UK weather observations and were obtained using regression and interpolation to generate values on a regular grid from irregular station network data at a 5 by 5 km grid scale (Perry *et al.*, 2009). The density of the station network used to generate these grid data varies through time from around 600 stations across the UK in the mid-1990s to around 450 stations in 2006. The interpolation takes into account latitude and longitude factors, including also the influence of the altitude and terrain shape, coastal impact and land use.

One of the main advantages of this dataset is that regional data can be produced for any given locality with a greater consistency and accuracy, being less reliant on the weather station network that can be irregularly spaced and change spatially over time (Met Office, 2009). The interpolated data provide credible estimates for points located at a distance from weather stations (such as the upland areas) and they have continuous time series with no missing values.

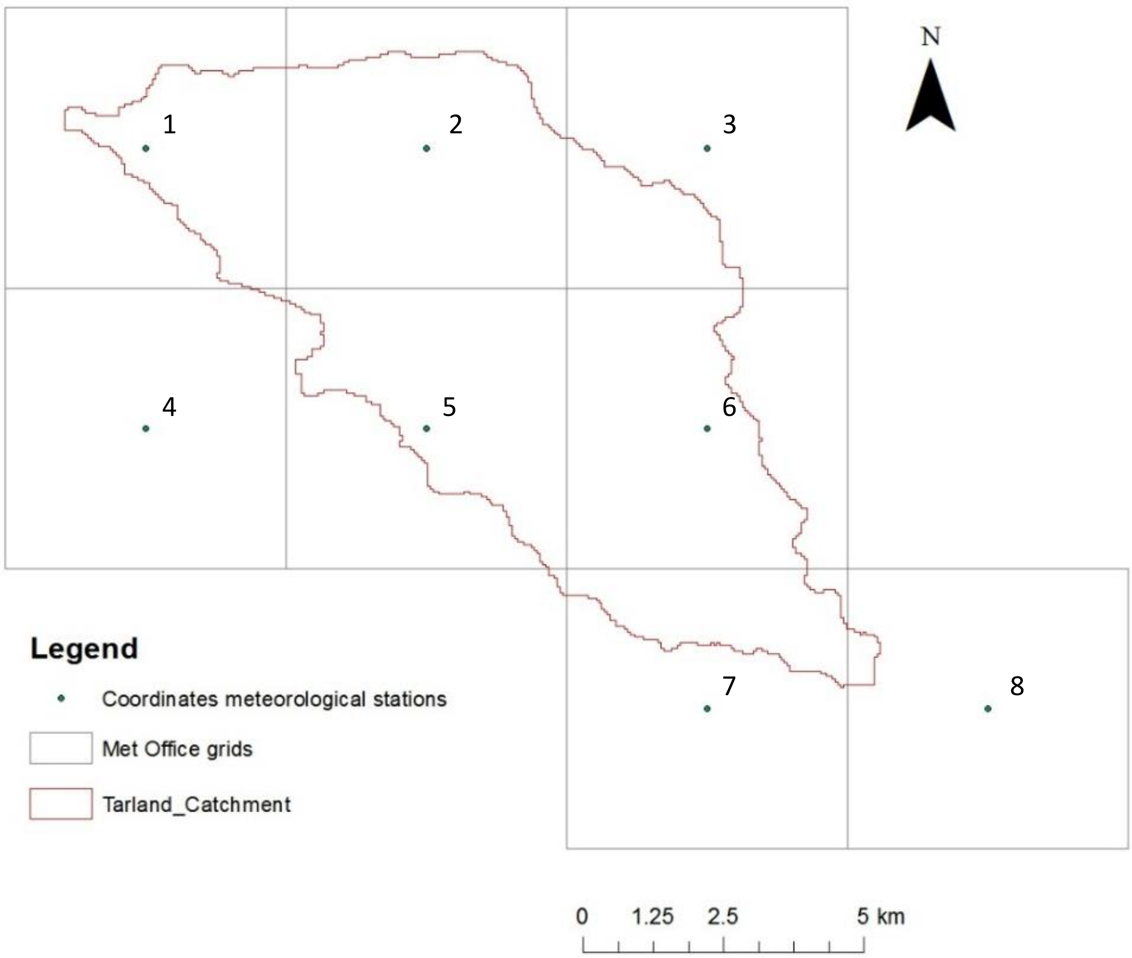

Figure 3.18. Met Office grids and coordinates for meteorological stations

There are eight 5x5 km grids that cover the Tarland catchment (as shown in Figure 3.18). The weather data for these grids are available at a daily time step, so they cannot be directly compared with the Aboyne station meteorological data.

Yearly rainfall totals were calculated for every 5x5 grid, using data for each year in the calibration-validation period (2005 to 2008), and comparing with the measured total annual precipitation at Aboyne. From Table 3.6 it can be seen that the largest differences are between Aboyne and the 1st, 2nd and 3rd squares, which cover the northern part of the catchment with the highest elevation. This is to be expected because a certain degree of under-catch has been reported for the Aboyne station, partly due to the location (external disturbances like trees, buildings). Aboyne is in the driest place in the catchment, so some degree of underestimation can be inferred when comparing to nearby upland areas.

Table 3.6. Annual rainfall totals for Aboyne and the 5x5 grid cells that cover the catchment

Year	Sq1	Sq2	Sq3	Sq4	Sq5	Sq6	Sq7	Sq8	Aboyne Obs
2005	937	978	908	747	790	862	748	726.9	759.4
2006	809	821	725	709	738	751	720	681.2	733.14
2007	1006	1052	964	863	928	967	897	824	931.24
2008	981	1022	973	784	795	872	769	791.9	738.52

Correction factors were calculated by dividing the grid totals for each square to the precipitation totals recorded at Aboyne station. As the difference between the gridded data and the data at Aboyne varies over time, the correction factors were calculated for each year separately and adjustments to the rainfall parameters were made accordingly (Table 3.7).

Table 3.7. Yearly correction factors for each 5x5 grid

Year	CF Sq1	CF Sq2	CF Sq3	CF Sq4	CF Sq5	CF Sq6	CF Sq7	CF Sq8
2005	1.151	1.202	1.116	0.918	0.971	1.059	0.919	0.893
2006	0.994	1.009	0.891	0.871	0.907	0.923	0.885	0.837
2007	1.236	1.293	1.185	1.060	1.140	1.188	1.102	1.013
2008	1.205	1.256	1.196	0.963	0.977	1.072	0.945	0.973

*CF - Correction Factor

There is a connection between the distance of the grid cell to the Aboyne meteorological station, and the value of the correction factor – the larger the distance, the higher the correction factor (see Figure 3.18). This is to be expected as the grids that are covering the upland areas are experiencing higher amounts of rain compared to the lower parts of the catchment where the Aboyne meteorological station is located (as discussed above). The rainfall for squares 1, 2 and 3 is constantly underestimated which is evidence of the rain shadow effect previously discussed.

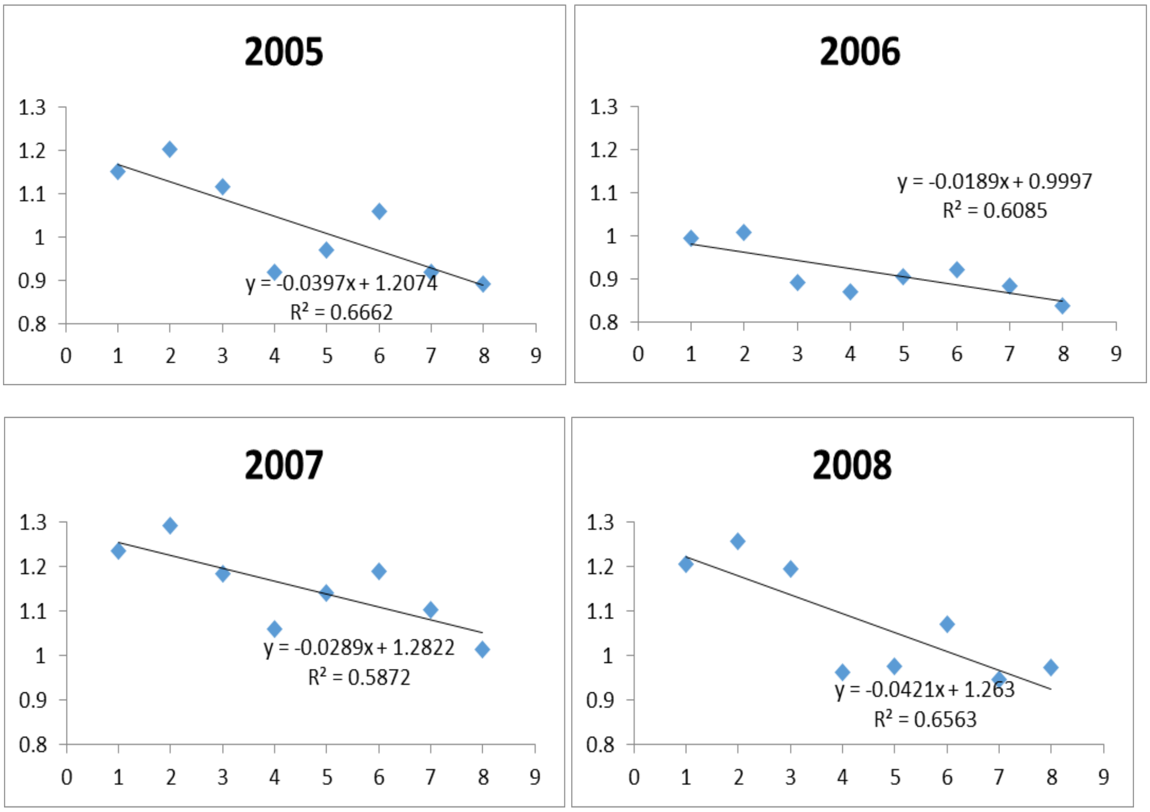

Figure 3.19. Correction factors for the network of grids and stations

Using these correction factors, a network of eight meteorological settings has been created, with location coordinates in the centre of the 5x5 grid cells.

3.7.2 Discharge data correction

Discharge data from Coull Bridge and Aboyne (SEPA) gauge stations were used for the calibration and validation phase of the modelling work. Tarland Burn at Coull Bridge station is draining approximately 72% of the catchment and approximately 98% at Aboyne. Calculating the discharge ratio of the Coull Bridge gauge to Aboyne (SEPA) gauge is a useful way of identifying any potential issue related to structural change at any of the stations. When calculating this ratio for the period 2005 to 2008, it could clearly be seen that the ratio changed at the beginning of 2007, with the largest differences seen through to 2008 (Figure 3.20). This was also reflected in the model results, which showed a significantly reduced discharge at Coull Bridge for 2007-2008 when compared to the measured discharge. The most common reasons for such a shift are (i) changes in the drainage system of the agricultural land or the settlements, (ii) loose sediments filling up the river at one of the stations (iii) other constructions at the gauge.

Changes in the river channel in late 2006 and throughout 2007 are noted by Sewell & Hutton (2010). High flows at Coull Bridge have resulted in a scour in the river bank, building sediments into the centre of the channel. It seems that the discharge is over-estimated for the 2007-2008 period, which is subsequent to the limitations of the rating curve at Coull Bridge (discussed in section 3.6.1).

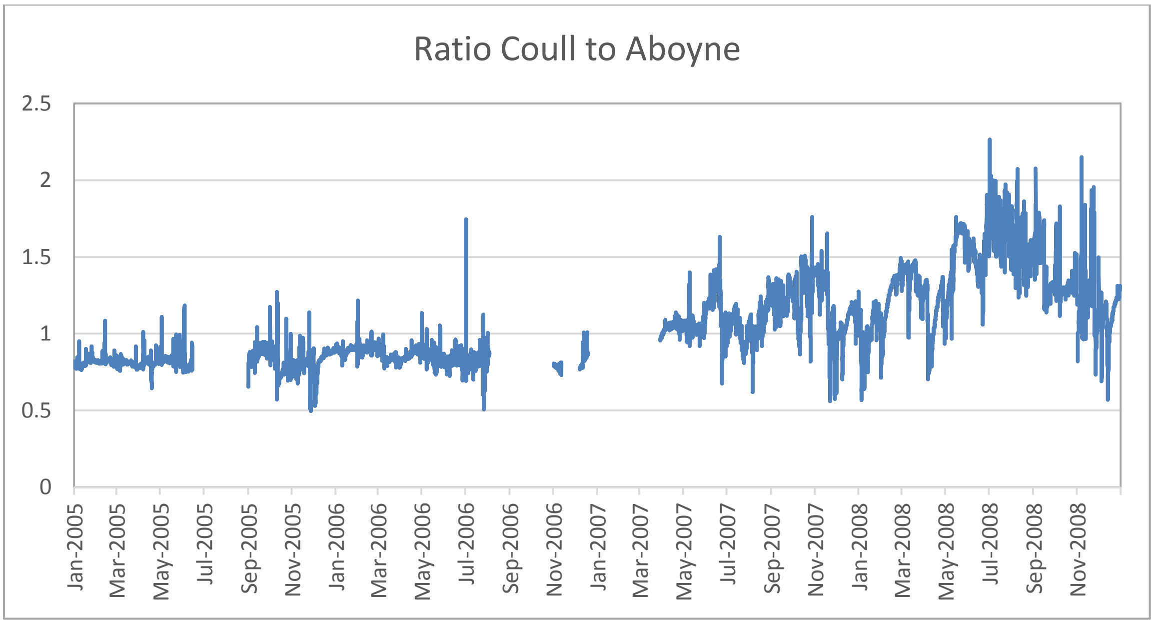

Figure 3.20. Ratio of discharge at Coull Bridge to discharge at Aboyne (SEPA) station

One way to correct discharge gauge data at an unreliable station is to find a correlation or a function between the unreliable station and a reliable station in closest proximity. This relationship is however likely to differ for low-flow events compared to high-flow events. This approach is particularly useful in catchments where there is only one gauge measuring the water levels, and establishing a relation with another gauge can be critical. However, since the discharge data at Aboyne (SEPA) station could be used for validation up to 2008, for the current study the analysis was not extended. Data for the year 2005 were used for the calibration and for 2006 for the validation at Coull Bridge, and data for 2005-2008 were used for the validation at Aboyne (SEPA) station.

3.8 Issues identified in the catchment

Intensive land management along with an expanding human population are the main drivers of change in Tarland catchment, which translate into a series of pressures on water quality and habitat impacting not only on the catchment but also on the wider River Dee further downstream (Figure 3.21). The pressures include (i) diffuse source pollution from agricultural runoff, (ii) wastewater from sewage treatment and from septic tanks and (iii) morphological alterations such as channelization, realignment and reinforcement. This leads to flooding, loss of habitat diversity and increased sediment content and microbial contaminants (The Macaulay Institute for Soil Research, 2008).

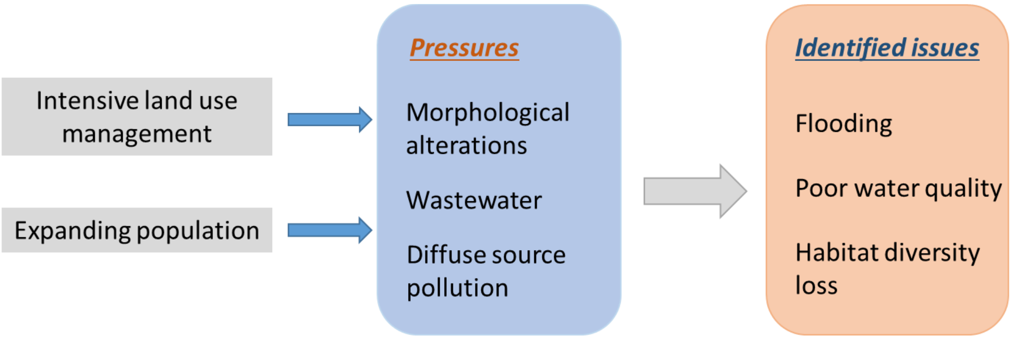

Figure 3.21. Pressures and environmental issues identified in Tarland Burn Catchment

The water quality within the catchment fails to meet the Good Ecological Status under SEPA's classification for the Water Framework Directive (WFD), due to high levels of nutrients (phosphorus) and adverse hydro-morphological characteristics (Stutter 2010). Tarland Burn is achieving only Moderate Ecological Status and it has been identified as being at significant risk of failing to meet the WFD quality target of Good Ecological Status by 2015. Remediation work in the catchment has focused on investigating the role of buffer strips in improving the water quality, which should facilitate the achievement of the good status by 2027 (Stutter *et al.*, 2009, 2012).

Figure 3.22. Tarland village (a) December 2013, (b) severe flood in October 2002

The Aberdeenshire Council Biannual Reports (Aberdeenshire Council, 1997, 1999, 2001, 2003, 2005, 2007, 2009) released under the Flood Prevention (Scotland) Act 1961 have been reporting floods both at Tarland and Aboyne. Over the period of 14 years covered by these reports, only one major event has been recorded in October in 2002, which occurred as a result of prolonged rainfall on wet soil conditions. This event affected the whole of Aberdeenshire, including the villages of Tarland and Aboyne (Figure 3.22). This led to the initialization of the Tarland Flood Prevention Scheme (TFPS), which has as a desired output a flood reduction in the catchment. The scheme includes owners and tenants, including non-farmers which have expressed an interest in flood mitigation measures on their land. In addition several other flood events have been recorded by Aberdeenshire Council, as presented in Table 3.8. Under the Flood Risk Management Act 2009 the Aberdeenshire Council is no longer required to release these biannual reports.

Table 3.8. Flood events in Tarland Burn catchment evidenced in different sources

Date	Location	Details	Action
April 2000	Tarland	Flooding of private dwellings and public road	Flood bank and river training wall constructed 2001/2002
April 2000	Station Square Aboyne	Flooding of commercial premises and public roads	Flood banks and non-return valves on outfall pipes to be constructed
October 2000	Ariel Villa, Tarland	Flooding of private dweling	Flood bank and River Training wall to be constructed 2001/2002
December 2000	Low Road Aboyne	Flooding of public road	Training wall constructed 2001/2002
October 2002	Burnside Road, Tarland	Burn overtopped and flooded domestic properties	
October 2002	Station Square/ Low Road Aboyne	Tarland Burn overtopped and flooded commercial and domestic properties (1 family evacuated)	
December 2005	Tarland South West field	Runoff from heavy rain on adjacent field caused fiel drains to back up causing domestic property to flood	Flood prevention scheme ongoing
March 2006	Burnside Road, Tarland	Heavy rain causes Tarland Burn to overtop and flood public roads	Flood prevention scheme ongoing
July 2006	Tarland/Migvie Road	Ponding of the public road. Runoff from heavy rain on adjacent field and woodlands	Local roads area installed additional road gullies
February 2009	Tarland	Runoff from overtopping. Flooding threatening many houses	
July 2009	Aboyne	Blocked gullies and road runoff. Two properties were flooded.	

An internet search for news reporting of flood events in the catchment from 2009 was undertaken and the results are presented in Table 3.9.

Table 3.9.Flood events in the catchment reported in different newspapers

Date	Paper	Location	Flooding source	Summary
July 2009	The Scotsman	Aboyne	Surface/sewer	Parts of Aboyne affected by floods after torrential rain
July 2009	Deeside Piper and Herald	Aboyne	Surface/sewer	Torrential rain let to some streets being less than six to eight inches of water
May 2010	Press and Journal	Aboyne	Surface/sewer	Torrential rain resulted at Rose Lodge Nursery along with a number of domestic properties. The road between Tarland and Aboyne was closed.
August 2011	BBC	Aboyne	Surface/sewer	Heavy rainfall led to localised floods
April 2013	River Dee	Aboyne	Surface/sewer	Large flood in the wider River Dee which affected Aboyne
December 2013	The Independent	Aboyne	Surface/sewer	Power cut in some residential properties at Aboyne due to floods

Over-abstraction and low flows are seen as a potential problem for Tarland in the future, as summers and autumns are expected to become warmer and drier. Lower levels in the streams will increase the pollutant concentrations due to lower dilution, with a direct impact on habitat quality and biodiversity (The Macaulay Institute for Soil Research, 2009).

3.9 Summary

Tarland Burn is a tributary of the wider River Dee situated in the North East of Scotland and it drains approximately 72 km^2. The fertile landscape made the catchment attractive for early setters with evidence of their presence dating back more than 4,000 years. Whilst the catchment has suffered significant changes in the last 200 years, there are fewer documented accounts of change before the 19^{th} Century. Surveys dating to the 1820’s and 1860’s confirm that significant drainage works were undertaken during that time period, to increase the access to land, and improve the agricultural yield. The catchment is now primarily managed for agriculture and cattle farming, the land cover being a mixture of grassland, woodland and arable land.

Hourly meteorological data are available at Aboyne station operated by the Met Office. There are four discharge gauge stations in the catchment. However, only data from Coull Bridge and Aboyne (SEPA) gauges were used for the study due to lack of data availability or reliability issues.

Several further issues have been identified with the meteorological data and discharge gauge data which have been addressed here. The meteorological station is located in the lower part of the catchment, characterized by lower altitudes and less rainfall, compared to the northern part of the catchment. To address this spatial discontinuity, the annual precipitation totals measured at Aboyne station were compared with Met Office grid data available for 5x5 km grid cells, and correction factors were calculated. The discharge data at the Coull Bridge gauge seemed to be overestimated due to structural change in the river channel. Floods in late 2005 and 2006 at Coull Bridge led to a build-up of sediments in the middle of the channel, causing a shift in the cross-section profile. Therefore, data for 2007-2008 at Coull Bridge station were not considered for the analysis.

The water quality in the catchment fails to meet the Good Ecological Status directed by the WFD. This is a result of diffuse pollution from intensive land management for agriculture in the catchment, along with an expanding population. Floods have been recorded in the area by the Aberdeenshire Council, with regular flood events both at Tarland and Aboyne villages. The catchment has attracted a lot of interest for research with a focus on water quality.

The next chapter presents the WaSiM-ETH hydrological model used for land use and climate investigation in the thesis. It includes a description of the main equations the model is based upon and details the calibration and validation process, along with a discussion of its overall performance.

Chapter 4. Hydrological modelling for land use management and climate investigations: model setup and model calibration

4.1 Introduction

Models have been widely used in assessing catchment behaviours and they are now achieving greater utility as they become more complex, allowing for a better representation of catchment processes (Beven, 2012). Modelling tools are necessary for investigations, as hydrological measurements are limited and there is a need to extrapolate from the available field measurements to larger landscape-wide scales. Whilst hydrological models are representing the main catchment's features in a simplified manner, they are valuable tools in assisting with data interpretation and exploring different land management scenarios, techniques and potential futures.

A simplistic classification divides hydrological models into lumped and distributed. Lumped models treat the catchment as a single unit with general state variables used to parameterize the main catchment processes (Beven, 2012). Distributed models make predictions that are distributed in space by dividing the catchment into a specific number of grid squares for which the state variable and parameters need to be specified. Whilst lumped models are extensively used because they are conceptually simple and easy to apply (Paudel *et al.*, 2011) such an approach would not be suitable in land use impact assessment studies where the spatial variability is a critical component. Distributed models allow the spatial representation of land use change effects and because of their (generally) physical basis it is possible to account for the changing characteristic of the catchment in an easier manner, by adjusting the parameter values which have a physical basis (Beven, 2012). This project required the use of a distributed model because it seeks to understand spatial variability and the adoption of spatially-targeted measures. This aim provided an initial criterion in selecting eight hydrological models for further evaluation.

This chapter explains the model selection exercise along with the description of the selected WaSiM-ETH model, as well as the steps undertaken to set it up and calibrate it, along with a discussion of its overall performance in terms of calibration and validation.

4.2 Model selection

The functionality and complexity of hydrological models played an important role in model selection. The relationships describing catchment processes, and the scale and time resolution on which the model is set up were key criteria in assessing model functionality. Model complexity refers to the estimated data, resources and the support available in operating the model.

The selected hydrological model needed to be one which could balance complexity and functionality to assist in the investigation of different spatial and scale issues in relation to NFM options through land use scenarios. The hydrological model must therefore be able to appropriately represent land use changes. To this end the model needs to be able to adequately represent the impact of land cover characteristics on infiltration conditions, groundwater recharge, baseflow and runoff generation. A review by Beckers *et al*. (2009) looked at suitability of different hydrological models to represent forest hydrology with a consideration of their application in climate change studies.

This project is focused on woodland expansion as a NFM option so the hydrological model had to be able to suitably represent forest hydrology. The model also needed to robustly allow the representation of climate change. The selected model should therefore be: (i) fully distributed to allow representation of spatial issues of woodland expansion, (ii) physically based to take into account the physical characteristics of the catchment, (iii) allow the representation of mixed topography and climatic regimes and (iv) suitable to simulate climatic changes. The full range of criteria used to select the most appropriate model for this project is provided in a comparison of model candidates (Table 4.1).

DHSVM is a physically based model developed at the University of Washington (Wigmosta *et al*., 1994). It is aimed at representing the effects of vegetation and topography on the hydrological response of the catchment. However it does not include a groundwater model and it has been used mainly to model mountainous areas.

Table 4.1. Assessment criteria for the selection of the hydrological model

No	General information			Model functionality						Model complexity			Limitations	References model application
	Name	Developer	Distributed	Able to represent forest hydrology	Small to medium catchments	Mixed terrain topography	Mixed climatic regimes	Time step	Able to represent climatic changes	Data availability	Resources (manuals and tutorials)	Technical support		
1	DHSVM	Univ of Washington	Fully distributed	Yes	Yes	Steeply sloped terrain	Yes	Hourly to daily	Yes	Yes	Limited manuals and tutorials	Just by special arrangements	No technical support is available unless specific arrangements are made; Typically used for mountains areas as it does not consider the groundwater component; the overall functionality in more gently sloped terrain and in setting with a substantial groundwater component is likely limited	VanShaar *et al.*, (2002), Waichler *et al.*, (2005), Westrick *et al.*, (2002)
2	RHESSys	University of California	Semi-distributed	Yes	Yes	Yes	Yes	Daily	Yes	Yes	Yes	Just by special arrangements	Complex with many parameters - difficult during sensitivity analysis. Limited access to training, only by special arrangements	Sanford *et al.*, (2007), Tague & Band, (2001)
3	WASIM-ETH	Eidgenossische Technishe hoschshule (ETH)	Fully distributed	Yes	Yes	Yes	Yes	Hourly to daily	Yes	Yes	Yes	Limited; from developers	Initially developed for alpine and sub-alpine regions it has since been used to model the impacts of land use and climate change in lowland areas	Jasper *et al.*, (2004), Niehoff *et al.*, (2002), Wriedt & Rode, (2006)
4	PREVAH	Eidgenossische Technishe hoschshule (ETH), SDC Swiss Flood Forecasting Assistance Project	Semi-distributed	Yes	Yes	Steep	Yes	Hourly	Yes	Yes	Yes	Limited; from developers	Applied just for mountains areas; forest hydrology not tested	(Gurtz *et al.*, 1999, Klok *et al.*, 2001)
5	Mike-SHE	DHI Water & Environment	Fully distributed	Medium	Yes	Gradual	No (rain or snow)	Hourly to daily	Yes	Yes	Yes	Yes	Complex and with high licence costs	(Feyen *et al.*, 2000, Refsgaard, 1997, Smerdon *et al.*, 2009)
6	Hydro Geosphere	University of Waterloo and Laval University	Fully distributed	Medium	Yes	Yes	Rain	Adaptive time step	Yes	Yes	Just manual	Limited; from developer	Mainly used to study groundwater surface water interactions and in stimulating the effects of roads on watershed hydrology with an emphasis on the interaction of roads with subsurface flow processes	(Ebel *et al.*, 2007, Mirus *et al.*, 2007)
7	TOPMODEL	Keith Beven (Lancaster Uiversity)	Semi-distributed	Medium	Yes (smaller than 1000)	Moderate topography	Rain and snow	Hourly to monthly	Yes	Yes	Yes	Limited	It does not allow investigations that require fully distributed configurations	(Cameron *et al.*, 2000, Quinn *et al.*, 1998)
8	SWAT	Jeff Arnold (USDA Agriculture Research Service)	Semi-distributed	Medium	Yes	Gradual	No (rain or snow)	Daily	Yes	Yes	Yes	Developers	Developed to predict the impact of management on water, sediment and agricultural chemical yields	(Gassman *et al.*, 2007

The Regional Hydro-Ecological Simulation System (RHESSys) is a GIS based model which combines a set of physically based process models and a methodology for partitioning and parameterizing the landscape (Tague & Band, 2004). It is a complex model and the technical support is available only through special arrangements with the University of Washington in the US.

WaSiM-ETH model was developed at the Eidgenössische Technische Hochschule Zürich (ETH) in Switzerland by Dr Jörg Schulla (Schulla, 1997). The model is fully distributed, calculating the water fluxes on a regular grid and simulating the discharge in catchments using a routing scheme. Though it was initially developed for alpine and subalpine regions, it has since been extended to accommodate hydrological investigations in lowland situations. It allows a good representation of forest hydrology and for a flexible scale and time setup.

The Precipitation Runoff Evapotranspiration Hydrotope (PREVAH) has been developed by ETH (Switzerland) alongside the WaSiM-ETH model. The model can be used to increase the understanding of spatial and temporal variability of hydrological processes (Viviroli *et al.*, 2009). It can be used for catchments with a complex topography and as with WaSiM-ETH it can also evaluate the hydrological impacts for future climatic scenarios. Whilst there are a series of similarities between this model and WaSiM-ETH, the PREVAH model uses a simpler conceptualization for the representation of runoff and groundwater processes and it was not tested in forest hydrology studies.

The MIKE-SHE model was developed from 1977 by three European organisations and has been further extended and distributed by the Danish Hydrological Institute (DHI). The model is a fully distributed, grid-based model capable of simulating the major processes in the hydrological cycle (Abbott *et al.* 1986). It incorporates multiple soil layers, a single vegetation layer and takes advantage of flexible model time steps. The model is of high complexity and its commercial nature means that there are high costs associated with its use.

The HydroGeoSphere model has been developed at the University of Waterloo (Therrien *et al.*, 2010). The model is of high complexity because of the way the subsurface flow is calculated. The model requires precipitation data for event simulation and potential evapotranspiration for long term simulations, and it does not explicitly represent vegetation. The model does not have a GUI interface and cannot be linked to GIS.

TOPMODEL is a hydrological model suitable for catchment scale studies (Beven 1997). It is based on a simple topographic description and runoff mechanism. It is a semi-distributed model which uses the upslope area and the local slope to calculate the wetness index (Beven *et al*., 1984; Beven, 1997). Model training is only available through special arrangements.

The Soil Water Assessment Tool (SWAT) is a catchment model that can be used to evaluate the impacts of different management schemes on water, sediment and agricultural chemical yields (Gassman *et al*., 2007). The model divides the catchment into multiple sub-catchments partitioned into hydrological response units (HRUs). The HRUs have homogenous land use and soil characteristics. However it cannot be used for mixed climatic regimes and its ability to model forest hydrology is limited.

The WaSiM-ETH model was selected for the project as it fulfilled each of the criteria required for the analysis of hydrological outcomes likely to arise under different land use and climate futures. The main strength of WaSiM-ETH lies in its ability to characterise a complex watersheds by explicitly accounting for spatial variability of the soil profiles and the land cover at the desired resolution, when making assessments of changes in precipitation and runoff over the recent past using historical data, and for use with land use change scenarios and climate change projections.

The model can adapt to spatial resolutions from a few centimetres to several kilometres and can accommodate simulations at time steps from minutes to several days. The model has been applied at various scales, from smaller (Gurtz *et al*., 2003; Ollesch *et al*., 2005, 2006), to larger scales (Jasper *et al*., 2002, 2004). It has two options for describing soil processes (i) Topmodel equations and (ii) Richards equations. The latter was used for this project as they allow the discretization of soil processes and accommodate a surface routing module.

4.3 Applicability of WaSiM-ETH model in land use and climate change studies

WaSiM-ETH has been extensively used to investigate the hydrological response of land use changes (Jasper *et al*., 2004; Krause *et al*., 2007b; Verbunt *et al*., 2005). Its performance in assessing a catchment's response to climate change has been demonstrated in a series of studies on agricultural systems and forests in Switzerland (Fuhrer *et al*., 2006; Jasper *et al*., 2004), alpine catchments (Gurtz *et al*., 2005) and in south west Germany (Gädeke *et al*., 2013; Niehoff *et al*., 2002). Whilst it was initially developed to investigate glacier hydrology (Klok *et al*., 2002) and has been largely used for alpine regions (Jasper *et al*., 2002; Kunstmann & Stadler, 2005; Marx & Kunstmann, 2006), it has also been successfully used at lower altitudes in Germany (Gädeke *et al*., 2013; Krause & Bronstert, 2007) and it has appropriately represented forest hydrology (Krause *et al*., 2007). The model has also been used to validate precipitation forecasting models by comparing them against measured precipitation and using forecasts as input data in the WaSiM-ETH hydrological model (Ahrens *et al*., 2003).

4.4 WaSiM-ETH model description

WaSiM-ETH contains modules to describe catchment process detailed in the Technical manual (Schulla, 2012). Model version 9.04.03 was used for this study. A brief description of the modules and basic equations relevant to this research is presented in Figure 4.1.

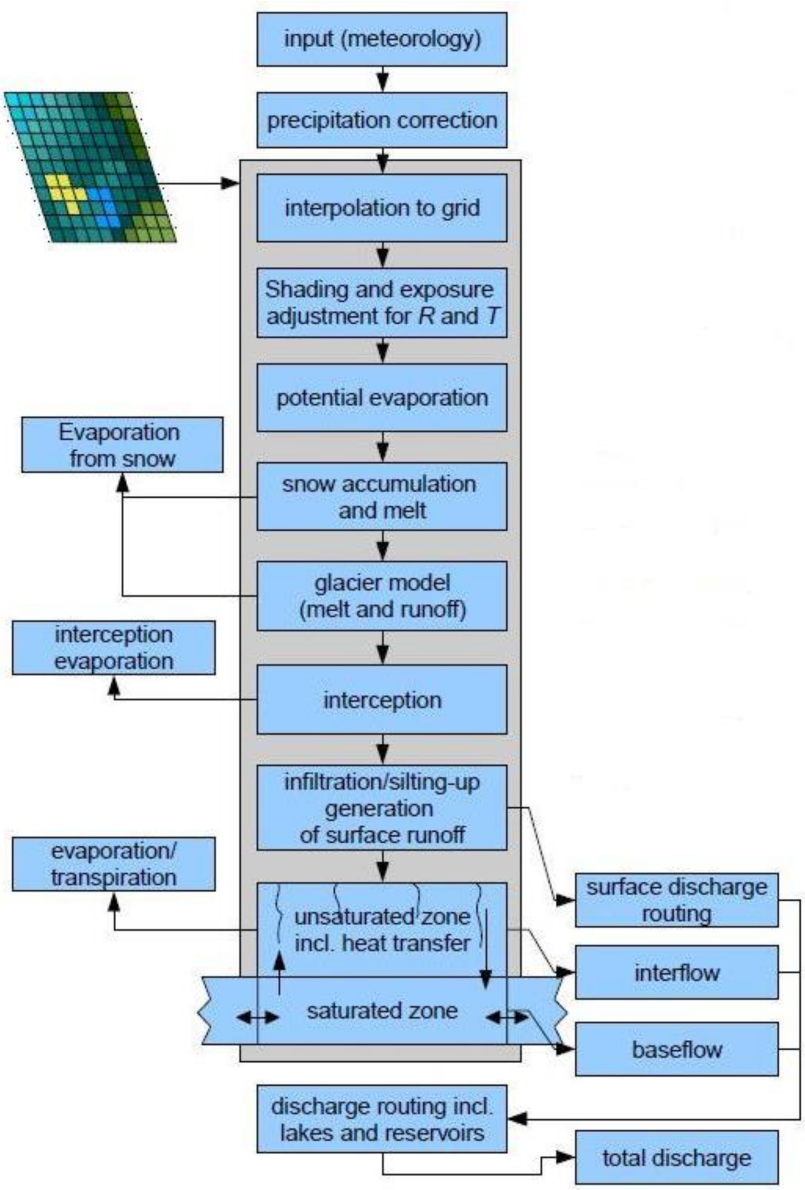

Figure 4.1. WaSiM-ETH model structure (Schulla, 2012)

4.4.1 Potential and actual evapotranspiration

Evapotranspiration is the process by which water is transferred from the land to the atmosphere; bare soils are responsible for evaporation and the plants available on different soil layer types are responsible for water uptake by transpiration, dependant on their properties and the moisture availability. The ability of the atmosphere to remove water from the surface through the processes of combined evaporation and transpiration, assuming no control on water supply is called potential evapotranspiration. The total amount of water that is actually removed from a surface due to the processes of evaporation and transpiration is the actual evapotranspiration.

In the WaSiM-ETH model the potential evapotranspiration is calculated internally using the Penman-Monteith approach considering up to three vegetation layers (Monteith, 1975). Evapotranspiration is computed by linearly reducing potential evaporation depending on the root zone potential (Feddes *et al.*, 1976).

This approach is recommended as it is the most sensitive to plant properties used for transpiration, which includes stomatal resistance, Leaf Area Index (LAI), effective height of the vegetation, distribution and depth of the rooting layer, vegetation coverage and the soil water content threshold below which transpiration starts to decrease. The Penman-Monteith equation (4.1) used to describe evapotranspiration (Monteith, 1965; Penman, 1948) in the WaSiM-ETH model is presented below.

$$\lambda \mathrm{E} = \frac{3.6\left(\frac{\Delta}{\gamma p}\right) \cdot (R_N - G) + \frac{\rho \cdot c_p}{\gamma_p \cdot r_a} \cdot (e_s - e) \cdot t_i}{\frac{\Delta}{\gamma_p} + 1 + \frac{r_s}{r_a}} \qquad (4.1)$$

Where: λ latent vaporization heat, λ=(2500,8-2,3752·T) [KJ·Kg^{-1}], T:temperature [^{o}C]

E latent heat flux [mm·m^{-2}]

Δ tangent of the saturated vapour pressure curve [hPa·K^{-1}]

R_N net radiation, conversion from Wh·m^{-2} to KJ·$^{-2}$ by a factor 3.6 [Wh·m^{-2}]

G soil heat flux [Wh·m^{-2}]

ρ density of dry air, $\rho=\frac{p}{R_L \cdot T}$, ρ=1.29 [Kg·$^{-3}$] at 0^{o}C and 1013,25 hPa

c_p specific heat capacity of dry air at constant pressure, c_p=1,005 [KJ·(Kg·K)$^{-1}$]

e_s saturation vapour pressure at the temperature T [hPa]

e actual vapour pressure (observed) [hPa]

t_i number if seconds within a time step

γ_p psychrometric constant [hPa·K^{-1}]

r_s bulk-surface resistance [s·m^{-1}]

r_a bulk-aerodynamic resistance [s·m^{-1}]

To calculate the actual evapotranspiration, the potential evapotranspiration is reduced by the amount of water equal to the interception storage of the plant canopy, followed by the reduction of potential evaporation based on the actual suction of the soil and physiological properties of the plant (Schulla & Jasper, 2000).

4.4.2 Interception

Interception is that part of the precipitation that does not reach the soil, being captured by the leaves and branches of plants and forest floor instead. To compute interception storage, a simple bucket approach is used in WaSiM-ETH. The interception is dependent on the total leaf coverage, which is a factor of LAI, and the maximum height of the water layer on the vegetation.

The equation (4.2) after Schulla (1997) is presented below:

$$SI_{max} = \upsilon \cdot LAI \cdot h_{SI} + (1 - \nu) \cdot h_{SI} \qquad (4.2)$$

Where SI_{max} maximum interception storage capacity [mm]

ν degree of vegetation coverage [m^2/m^{-2}]

LAI leaf area index [m^2/m^{-2}]

h_{SI} maximum height of water [mm]

The extraction of water by evaporation out of interception storage is considered at a potential rate in the model. If there is a sufficient amount of water held in storage, the storage content is reduced by the potential evaporation, and no evaporative water will be lost from the soil. If the storage content is smaller than the potential evaporation rate, the remaining content will be removed from the soil, as long as the soil is not too dry or too wet.

Based on this assumption, the interception evaporation will be:

$$EI = ETP \text{ (for SI} \geq \text{ETP in mm)}, \quad ETR = 0 \qquad (4.3)$$

$$\text{and } EI = SI \text{ (for SI} < \text{ETP in mm)}, \quad ETR = ETP - SI \qquad (4.4)$$

Where EI interception evaporation [mm]

ETP potential evaporation [mm]

ETR remaining evaporation from soil and vegetation [mm]

SI content of the interception storage [mm]

4.4.3 Snow module

The snow module in WaSiM-ETH simulates the melting and the accumulation of snow and how it contributes to the catchment's water balance. The fraction of snow from the total precipitation is presented below by equation 4.5. The type of precipitation is estimated for each grid cell using the interpolated air temperature. Both rainfall and snow can occur in the same time within the transition range.

The temperature-index approach was used to describe snow melt according to equation 4.5.

$$M = c_0 \cdot (T - T_{0,m}) \cdot \frac{\Delta t}{24} \qquad (4.5)$$

Where M melting rate in mm per time step

C_0 temperature dependent melt factor [$mm \cdot C^{-1} \cdot d^{-1}$]

T air temperature [^oC]

$T_{0,m}$ temperature for beginning snow melt [^oC]

Δt time step [h]

4.4.4 Infiltration and the unsaturated zone model

Using the modified approach developed by Green & Ampt (1911), excess infiltration feeds directly to runoff, and the amount of infiltrating water serves as an upper boundary condition in the unsaturated zone module.

Equation 4.6 is describing the calculation of infiltration. If PI>ks

$$t_s = \frac{l_s \cdot n_a}{PI} = \frac{\frac{\psi_f}{\frac{PI}{k_s} - 1}}{PI} \qquad (4.6)$$

Where t_s saturation deficit from the beginning of the time step [h]

l_s saturation depth [mm]

n_a fillable porosity ($n_a=\Theta_s-\Theta$) [-]

ψ_f suction of the wetting front (a≈1000n) [mm]

PI precipitation intensity [$mm \cdot h^{-1}$]

K_s saturated hydraulic conductivity [$mm \cdot h^{-1}$]

The water infiltrated until time F_s is calculated as:

$$F_s = l_s \cdot n_a = t_s \cdot PI \qquad (4.7)$$

Using the formula developed by Peshke (1989), the accumulated infiltration after saturation that has been reached due to percolation for one time step, is determined as:

$$F = \frac{A}{2} + \sqrt{[\frac{A^2}{4} + AB + F_s^2]} \qquad (4.8)$$

Where:

$$A = K_s(t - t_s)$$
$$B = F_s + 2 \cdot n_a \cdot \psi_f$$

The vertical movement of water in the soil is assumed to be one-dimensional within the unsaturated zone so no exchange of water is taking place between neighbouring cells. The cells are divided into different layers, their thickness defined in the soil table. Percolation and capillary rise determined by the soil properties are simulated with corresponding vertical moisture profiles and fluxes. The van Genuchten equation for a soil-water retention curve is used to include the hydraulic conductivity with decreasing water content (Van Genuchten 1980). The water release curve of soils is a function of the saturated (Θs) and residual (Θr) soil water content, the soil matrix potential ψ and the parameters α and n with the assumption that the hydraulic head and conductivities depend on the van Genuchten principles (1980).

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{(1 + (\psi\alpha)^n)^m} \qquad (4.9)$$

Where Θ actual water content [-]

ψ suction [hPa]

Θ_r residual water content at $k(\Theta)=0$ [-]

Θ_s saturation water content [-]

α,n empirical parameters (m=1-1/n) [-]

Linear storage approaches are applied to interflow and direct runoff, requiring the calibration of the recession constants for direct runoff (KD) and for interflow (KI) due to flow retention. The runoff at time t, (Qt) is a function of the runoff component at the initial time t_0, (Qt_0) and the corresponding recession constants K, calculated after equation 4.10.

$$Q_t = Q_{t_0} \cdot e^{\frac{\Delta t}{k}} \qquad (4.10)$$

Where change in time $\Delta t = t - t_0$

Interflow is generated between soil layers and is dependent on the suction and the drainage density of the soil. Groundwater recharge is calculated as the balance of inflows and outflows over the total number of layers to which the groundwater table contributes.

4.4.5 Groundwater module

Groundwater flow processes are described using a 2-D Darcy groundwater module presented below (4.11). The water storage at time t for a specific cell equals the balance of the inflows into and outflows out of the control volume. The model is multi-layered, the coupling between the layers is achieved using leakage factors.

$$div(T\ grad\ h) + q + l_{up}\left(h_{up} - h\right) + l_{lo}(h_{lo} - h) = S_0 \frac{\partial h}{\partial t} \qquad (4.11)$$

With T transmissivity [m^2/s]

h hydraulic head in the control volume [m]

q boundary fluxes perpendicular to the grid cell surface [m/s]

l_{up} leakage factor for fluxes between the actual and the upper aquifer [s^{-1}]

h_{up} hydraulic head in the upper laying aquifer [m]

l_{lo} leakage factor for fluxes between the actual and the lower aquifer [s^{-1}]

h_{lo} hydraulic head in the lower laying aquifer [m]

S_0 specific storage coefficient [l/l]

T time [s]

4.4.6 Artificial drainage

The parameterization of artificial drainage is achieved using information on the depth of the drainage tiles and the horizontal distance between drainage devices. The water outflow from artificial drainage is calculated separately and added to the interflow of the same layer when quantifying influx into the unsaturated zone. Thus drainage can affect also the downwards water flow from the layers above. The drainage water is calculated after equation 4.12.

$$q_{drain} = k(\Theta) \cdot \frac{2d_m}{d_h} \cdot \frac{cs}{d_h} \qquad (4.12)$$

Where q_{drain} drainage from layer m, if drainage tiles or hoses are located in this layer [m/s]

$K(\Theta)$ hydraulic conductivity as a function of water content and soil type

d_m layer thickness of the drainage layer m (discretization in z direction) [m]

d_h horizontal spacing of drainage tiles [m]

cs grid cell size [m]

4.4.7 Runoff routing

The WaSiM-ETH hydrological model is a water balance models and so the outputs are not defined by channel configuration. The generated runoff in each cell is directed to the outlet of a basin, with respect to flow times that are calculated by the pre-processor Topographical Analysis (Tanalys) for the entire catchment, and considering the distances to specific routed outlets. These flow times are calculated using the Manning-Strickler equation (Schulla & Jasper, 2000). Flow velocities for the different water levels in the channel are calculated using both a kinematic wave approach and simple linear storage approach. Thereafter, direct runoff and interflow are simulated.

4.5 Efficiency coefficients

4.5.1 Nash-Sutcliffe efficiency index

The Nash-Sutcliffe index (NSE) is a statistic widely used for assessing the goodness of fit of hydrological models. The quality of model calibration and validation was measured using an efficiency criterion proposed by Nash & Sutcliffe (1970), which represents a widely used 'goodness-of-fit' measure in hydrological modeling (Legates & Mccabe, 1999; Wertz-Kanounnikoff *et al.*, 2011). It is given by:

$$NSC = 1 - \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (4.13)$$

Where xi observed discharge

Yi modelled discharge

$\bar{x}$ mean of observed discharge

4.5.2 Nash-Sutcliffe efficiency with logarithmic values

To reduce the problem of the squared differences leading to sensitivity to extreme values, the Nash-Sutcliffe efficiency is often calculated with logarithmic values (ln) of the measured and modelled discharge. Through the logarithmic transformation of the runoff values the peaks are flattened and the low flows are kept more or less at the same level. As a result the influence of the low flows is increased in comparison to the flood peaks, resulting in an increase in sensitivity of ln NSE to systematic model over or under predictions (Krause *et al*., 2001).

4.5.3 Pearson's r and R^2

Pearson's correlation coefficient (r) and coefficient of determination (R^2) describe the degree of collinearity between simulated and measured data. The Pearson product-moment correlation coefficient typically noted with r is a measure of linear correlation between two variables X and Y which can take values between the range -1 (total negative correlation) and +1 (total positive correlation). If r = 0, no linear relationship exists. If r = 1 or −1, a perfect positive or negative linear relationship exists. From paired data (Xi, Yi), the sample Pearson correlation coefficient is calculated as:

$$r = \frac{\sum_{i=1}^{n}(X_i - \overline{X})\,(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\,\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \qquad (4.14)$$

Where $\overline{X}$ and $\overline{Y}$ are representing the sample means of X and Y.

The R^2 statistic measures the fraction of the total variability in the response compared with that accounted for by the model and ranges between 1 (perfect fit) to 0 with values greater than 0.5 typically considered acceptable (Moriasi *et al*., 2007).

4.6 WaSiM-ETH use in Tarland Burn catchment

WaSiM-ETH was applied in the Tarland Burn catchment at a spatial and time resolution that allowed the best use of the spatially distributed data, time series meteorological data and hydrological data. Spatial data and temporal meteorological station input data (see Table 4.2) are required to run the model, with the initialization and parameterization resolved using a control file. The efficiency coefficients were calculated for each calibration step and if the results were not satisfactory (i.e NSE less than 0.5), a data refining step was undertaken before running another set of simulations and calculating the efficiency coefficients (according to Figure 4.2).

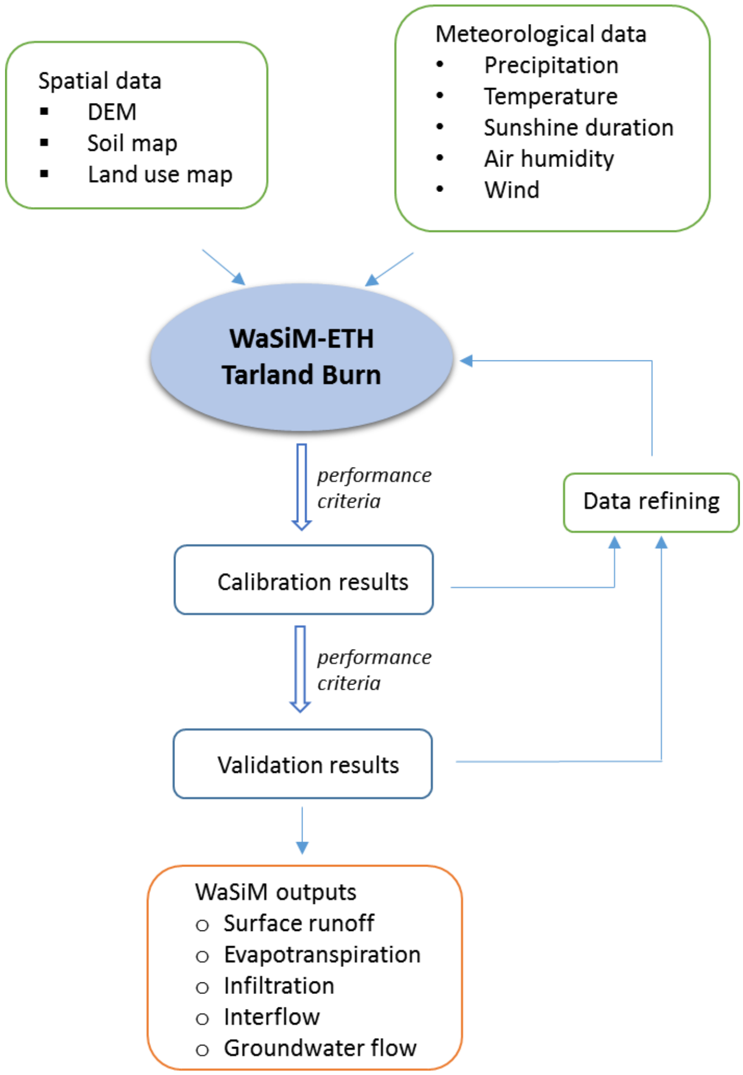

Figure 4.2. WaSiM-ETH model for Tarland Burn catchment

4.6.1 Input data

To investigate the flood risk in Tarland Burn catchment the model was setup on an hourly time step and all spatial data configured at a 50 by 50 meter grid scale. The main input datasets are presented in Table 4.2.

Table 4.2. Input data for setting up WaSim-ETH model for Tarland Burn Catchment

Input data	Datasets	Source	Resolution / time series length
Spatial data	DEM	Land-Form PROFILE	50 x 50 m
	Soil map (1:25000)	James Hutton Institute (Scottish Government funded project)	
	Land use map	Land Cover Map 2007	
Temporal data	Precipitation	Aboyne 2 station	01.01.2005-31.12.2008
	Temperature	Aboyne 2 station	
	Wind	Aboyne 2 station	
	Sunshine	Ballatar station	
	Air humidity	Aboyne 2 station	

4.6.1.1 Spatial data

Digital Elevation Model

The Digital Elevation Model (DEM) was derived from the Land-Form PROFILE. The Land-Form Profile provides detailed height information which defines the physical shape of the landscape in Great Britain. The contours were originally surveyed using photogrammetry, a stereo image interpretation and supplied as published mapping. To derive the Land-Form PROFILE data, digital contours are interpolated onto a regular grid to produce a DEM. The dataset was updated on the 1st of January 2014, however because the model was developed prior to 2014, the previous version was used for the study (Ordnance Survey, 2012).

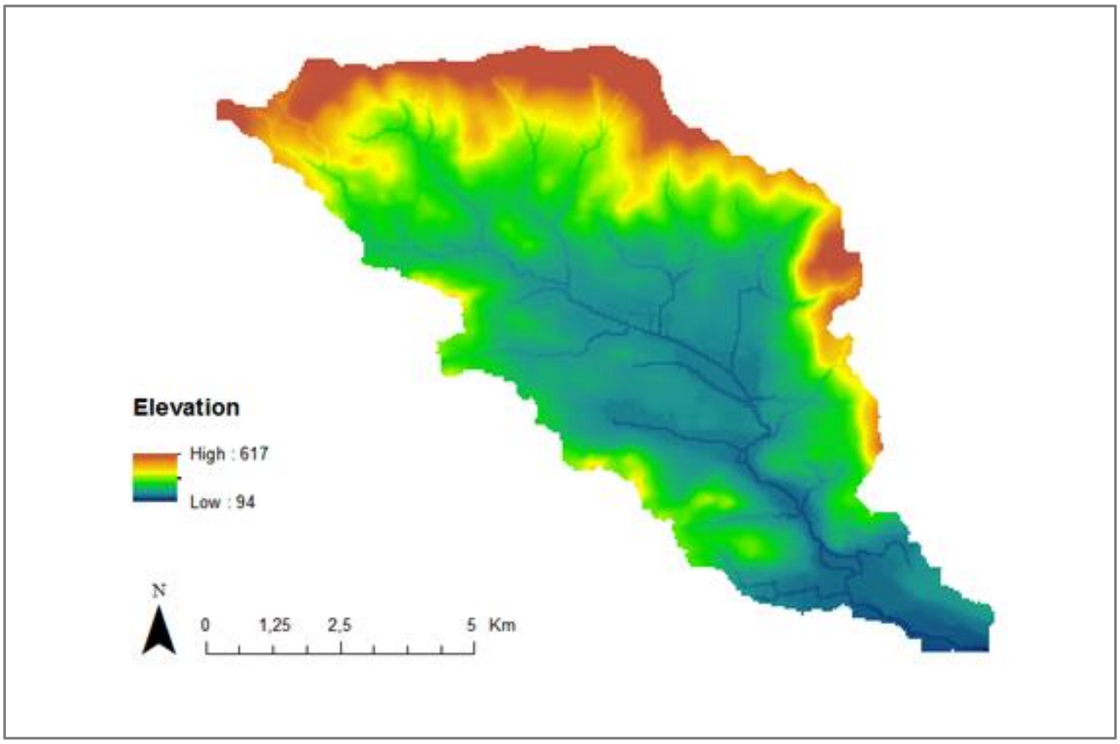

Figure 4.3. Physiography of the Tarland Burn catchment (elevation: meters above sea level)

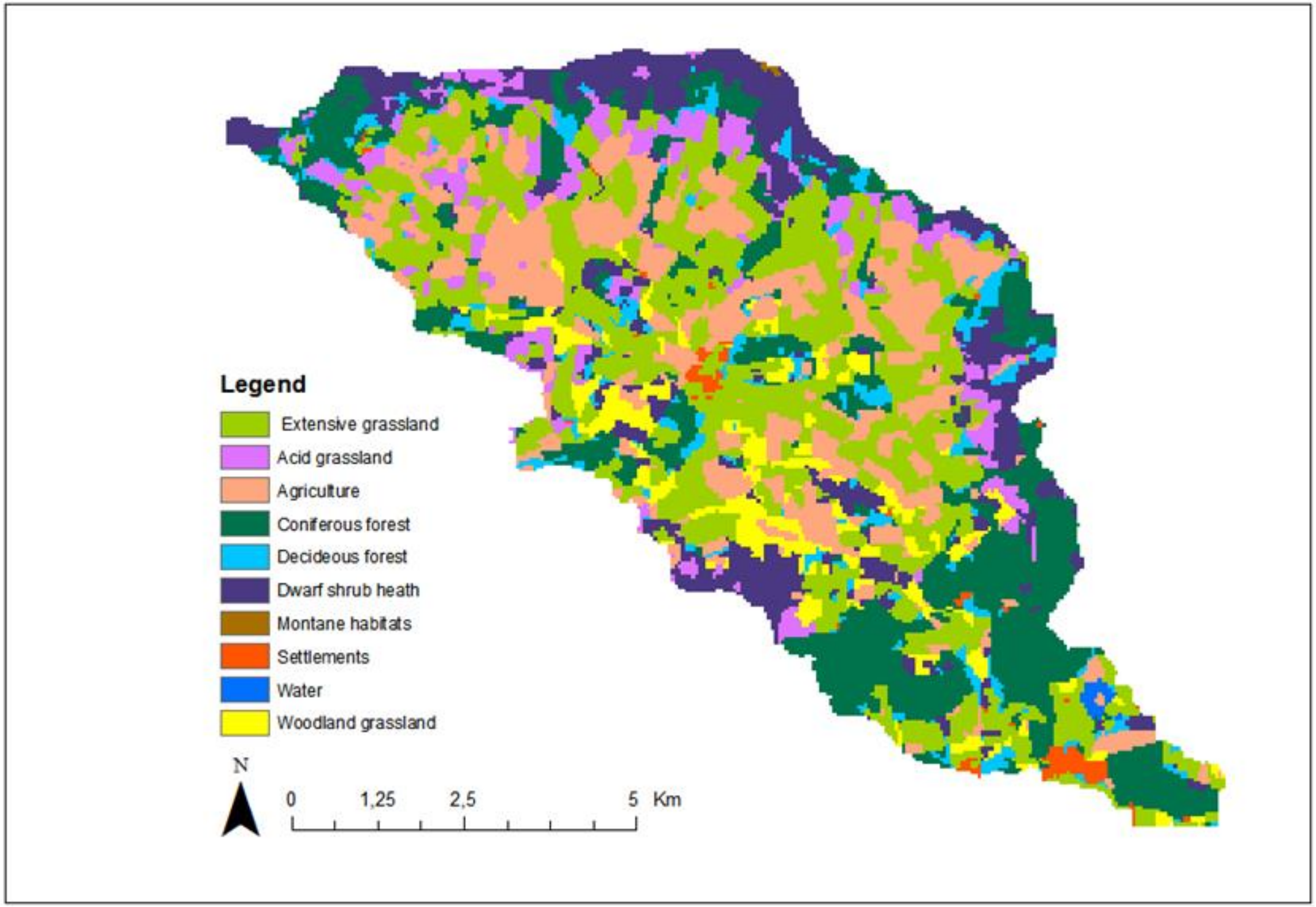

Figure 4.4. Tarland Burn catchment land cover map from LCM2007

Land use and land cover

The land use map used in the project was the Land Cover Map 2007 (LCM2007), the third in the Land Cover Map series (see Figure 4.4). The LCM2007 maps twenty three land cover classes across UK with ten of these present in the Tarland Burn catchment. LCM2007 is the first UK land cover map with land parcels derived from national cartography by a simplification process. It is based on Ordnance Survey Master Map topography and it was produced from more than seventy satellite images combined in 34 multi-date summer-winter images (Morton *et al.*, 2011). At the start of the project this was the most recent land cover map available for Tarland so it was selected for the project. The vector map was converted to a 50 m by 50 m grid cell.

Soil map and soil texture

The soil map for the whole of Scotland is the result of a two year project funded by the Scottish Government in partnership with SEPA, SNH and Forestry Commission Scotland and it displays the distribution of different soil types based on multiple criteria. Soils are mapped at different scales and this influences the level of detail that can be represented, i.e. smaller scale maps (e.g. 1:250,000) can show less detail than larger scale maps (e.g. 1:2500). The vector map at 1:25 000 scale was converted to a 50 by 50 m grid cell (The Macaulay Institute for Soil Research, 1984).

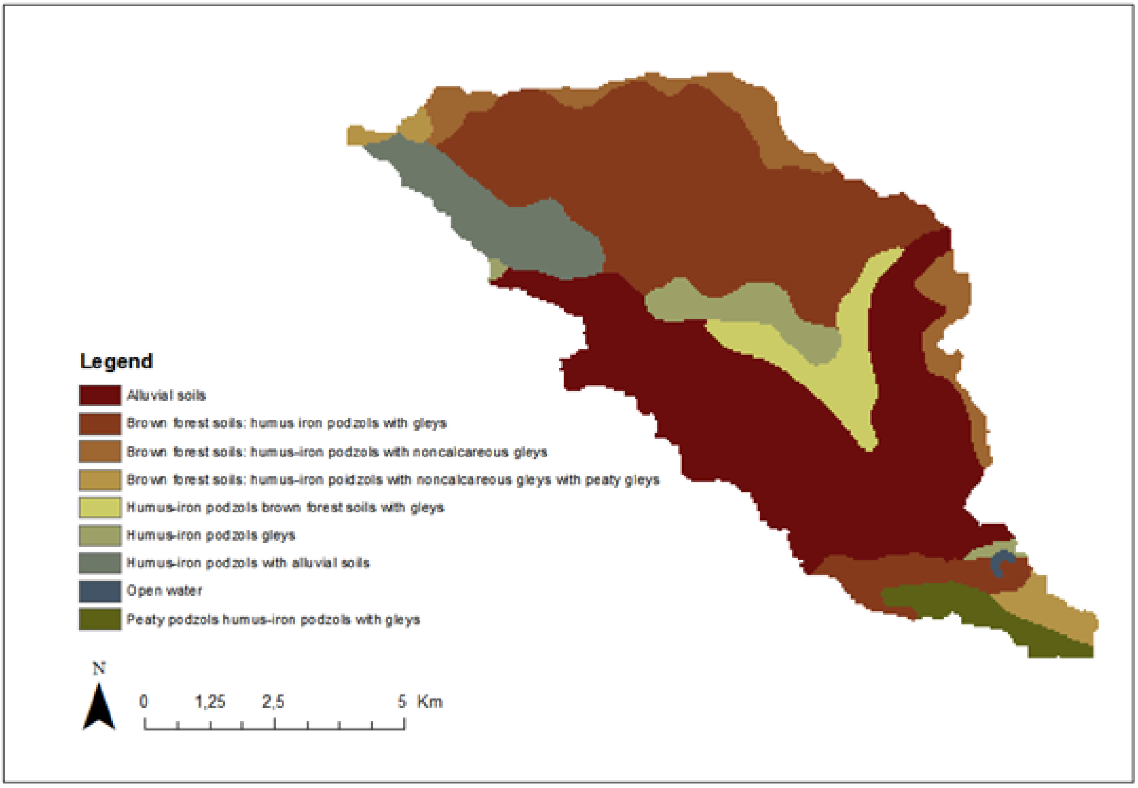

Figure 4.5. Soil map Tarland Burn catchment

Pedo-transfer function

Pedo-transfer functions (PTF) are predictive functions of soil properties derived from a set of survey data (Pachepsky & Rawls, 2004). There are different regression analyses and data mining techniques to extract rules which associate basic soil properties with other more costly determined soil properties. The Rosetta software used for this project offers five PTFs that allow prediction of the hydraulic properties with limited or more extended sets of input data. The selected model requires as input the percentages of sand, silt and clay and is based on neural network analyses. Uncertainty estimates are provided for all estimated hydraulic parameters, allowing an assessment of the accuracy of the predictions. In Rosetta, the uncertainty estimates for the soil hydraulic conductivity are generated by linking the neural networks with the bootstrap method (Schaap & Leij; 1998, Schaap *et al*., 1999).

4.6.1.2 Temporal data

Rainfall, temperature, relative humidity and wind data were taken from the Aboyne Met Office station located 5 km outside of the catchment's boundaries (see Figure 4.6). Sunshine duration data were not recorded at Aboyne station, so data from the more distant Braemar station were used instead. This station was chosen because it is the closest to Aboyne available under similar meteorological conditions. Rainfall data have the greatest impact on the discharge model outputs. These data however are subject to errors, both instrumental errors during measurements and human errors during readings and manipulations. The WaSiM-ETH model has a precipitation correction module and its parameters are subject to calibration. Radiation and temperature also require some adjustment to compensate for a shading effect due to topography. The model is thus incorporating the influence of the topographic data using Oke's (Oke, 1987) method to determine temperature and radiation inputs using DEM information.

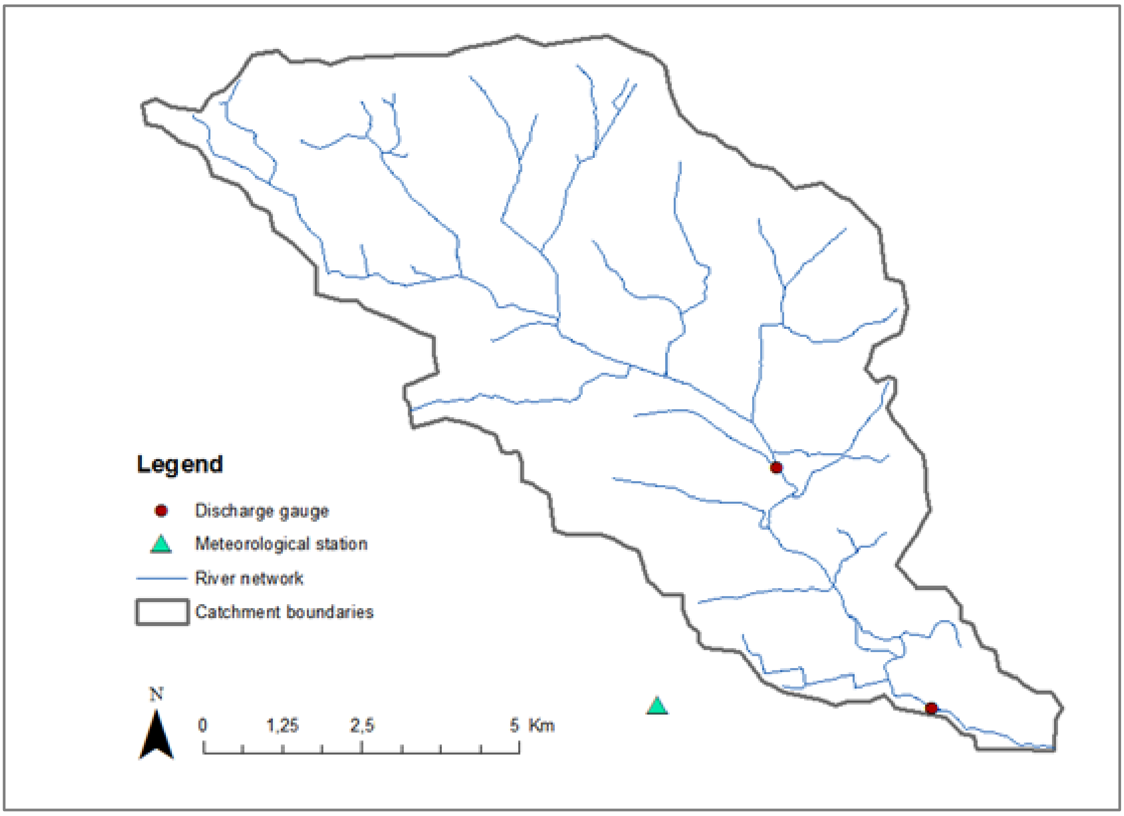

Figure 4.6. Hydrological and meteorological measuing stations in Tarland Burn catchment

The model offers several options for the interpolation of the meteorological parameters, the simple Thiessan approach was used, as there was only one meteorological station available recording at an hourly time step in close proximity to the catchment (cf. Shaw *et al.*, 2011).

4.6.2 Model setup

The model was set up on a 50 by 50 meters grid cell and for an hourly time step. A spatial resolution using a 10 m by 10 m grid cell was initially tested, however due to computational constraints and availability of data, the 50 meter grid cell was considered more appropriate. The hourly time step is necessary when investigating flood risk management options, which require analysis of time to peak and flow peaks. To parameterize and define the input data, the model uses a control file (see Appendix B). To compare among the initial conditions and changes to parameters in different calibration stages the control file needs to be modified to re-run the model.

WaSiM requires a pre-processing phase using the Tanalys tool. The pre-processor is used to calculate basin boundaries, stream network and flow times using the topographical information. The tool processes the spatial raster data into a binary input format required for WaSiM-ETH model. The topographic analysis is constrained by a control file similar to a WaSiM control file. There are a series of parameters controlling the extent of the analysis and a set of threshold values or constants need to be specified. The Manning Strickler value was defined as a single averaged value for the whole catchment. Schelle and Spende parameters control the generation of the river network and river depth and width. The DEM map and the file with the discharge gauges location need to be converted to binary format and their names and pathways need to be defined in the control file.

Table 4.3. Parameters Tanalys pre-processing tool

Inputs	Value
Manning	Manning Strickler topography roughness coefficient
Schwelle	The number of raster cells required to generate a river cell
Spende	Water yield of the catchment that is the quotient of runoff and catchment size ($l/s \cdot km^2$)

Land cover influence

Soil properties have a crucial role in runoff generation and water retention. Understanding the influence of land cover on soil properties is very important for achieving a good representation of the catchment. The close link between soil properties and land cover and its potential effects on flooding, has been investigated by a series of studies (Bens *et al.*, 2006; Hümann *et al.*, 2011; Robinson *et al.*, 2003). It does seem however that the influence of land cover on flood generation is larger for convective rainfall events than for long lasting advective precipitation events with moderate rainfall within meso-scale catchments (Bronstert *et al.*, 2002).

To represent the land cover influence on soil properties the hydraulic conductivity was used as a proxy. Therefore, the land cover types were assigned to four categories: (i) Arable, (ii) Grassland, (iii) Dwarf shrub and montane habitats and (iv) Woodland (see Table 4.4). The age of the different land cover, particularly forest, is an important factor in determining the influence of soil properties (cf. Archer *et al.*, 2013). The relation between land cover and soil properties is dynamic and susceptible to change over time. However, in the absence of very detailed data over a very long period of time it would be impossible to reflect temporal change in the model, so an assumption needs to be made in representing the vegetation age. To reflect the impact of a fully matured forest, it was considered that the forest vegetation exceeds the operational phase of afforestation, i.e. established for over 50 years.

Table 4.4. Matrix for changes in the saturated hydraulic conductivity (ks) representing land cover influence on soil properties

Soil type	Name soil	Averaged ks (ms^{-1})	Arable (A)	Grass (G)	Dwarf shrub & montane habitats	Woodland
1	Humus-iron podzols: brown forest soils with gleys	6.19E-06	A	A*2	G*2.5	G*4
2,12,14	Brown forest soils soils: humus-iron podzols with noncalcareous gleys with peaty gleys	4.61E-06	A	A*2	G*2.5	G*4
3,5,15	Humus-iron podzols: brown forest soils with gleys	5.01E-06	A	A*2	G*2.5	G*4
4,7	Peaty podzols: humus-iron podzols with gleys	1.08E-05	A	A*2	G*2.5	G*4
6	Brown forest soils: humus-iron podzols with gleys	6.11E-06	A	A*2	G*2.5	G*4
8	Alluvial soils	3.54E-06	A	A*2	G*2.5	G*4
9,10,11	Humus-iron podzols: gleys	1.98E05	A	A*2	G*2.5	G*4
13	Open water	4.00E-06	A	A*2	G*2.5	G*4
16	Humus-iron podzols with alluvial soils	3.15E-05	A	A*2	G*2.5	G*4

*Coefficients based on Archer *et al.* (2013) and Jarvis *et al.* (2013)

As a result of agricultural intensification soils most arable soils ar highly degraded in UK (Skinner *et al.*, 1997) Soil compaction (Håkansson *et al.*, 1988; Whalley *et al.*, 1995), soil erosion (Brazier, 2004) and loss of organic matter (Dobbie *et al.*, 2011) are major issues for arable soils. Most soils in Scotland are not managed intensively except for the eastern Scotland where soils are suitable for arable farming and tend to have high crop yields (Dobbie *et al.*, 2011). Studies have shown that arable land cover has no significant influence on the soil hydraulic properties, partly because of the short roots and seasonal variation. Thus the hydraulic conductivity is more dependent on the soil structure than the land cover (Gonzalez-Sosa *et al.*, 2010). For grassland the hydraulic conductivity is noted by Archer *et al.* (2013) and confirmed by Jarvis *et al.* (2013) to increase up to two times compared to arable landcover. The dwarf shrub and montane habitats cover has a similar impact as grassland on a soils' hydraulic properties. Deciduous and coniferous forest were not distinguished, simplifying the matrix, and consistent with Jost *et al.* (2012) who showed no significant variability for different tree species on soil properties in a study located in Lower Austria. Soils under natural forests are generally porous and have high infiltration rates. Therefore, forests have the potential to lower the surface runoff rates by influencing the water retention capacity. Tree roots loosen the soil and thus increase the overall water storage capacity, buffering the effect of rainfall on flood generation and reducing flood peaks (Hümann *et al.*, 2011). Forest cover has the highest impact on soil properties (Archer *et al.*, 2013; Jarvis *et al.*, 2013) with a hydraulic conductivity that is around four times higher than that of grassland.

Drainage density

Surface and subsurface drains in Tarland were set in place as early as the 1840s. The most significant changes have been made in areas around the village and on the agricultural plain, aiming to reduce waterlogging in order to increase access to land for an improved agricultural yield. The surface drains have been mapped based on the present OS Master Map (see Figure 4.7); however information on the subsurface drains are not available, as records of their location were not kept when they were first set in place. Having acknowledged that the drainage information used in the model are not complete, analysing the impacts of drainage is of significant value in contributing to the debate on whether drainage and drain blocking is beneficial for flood risk.

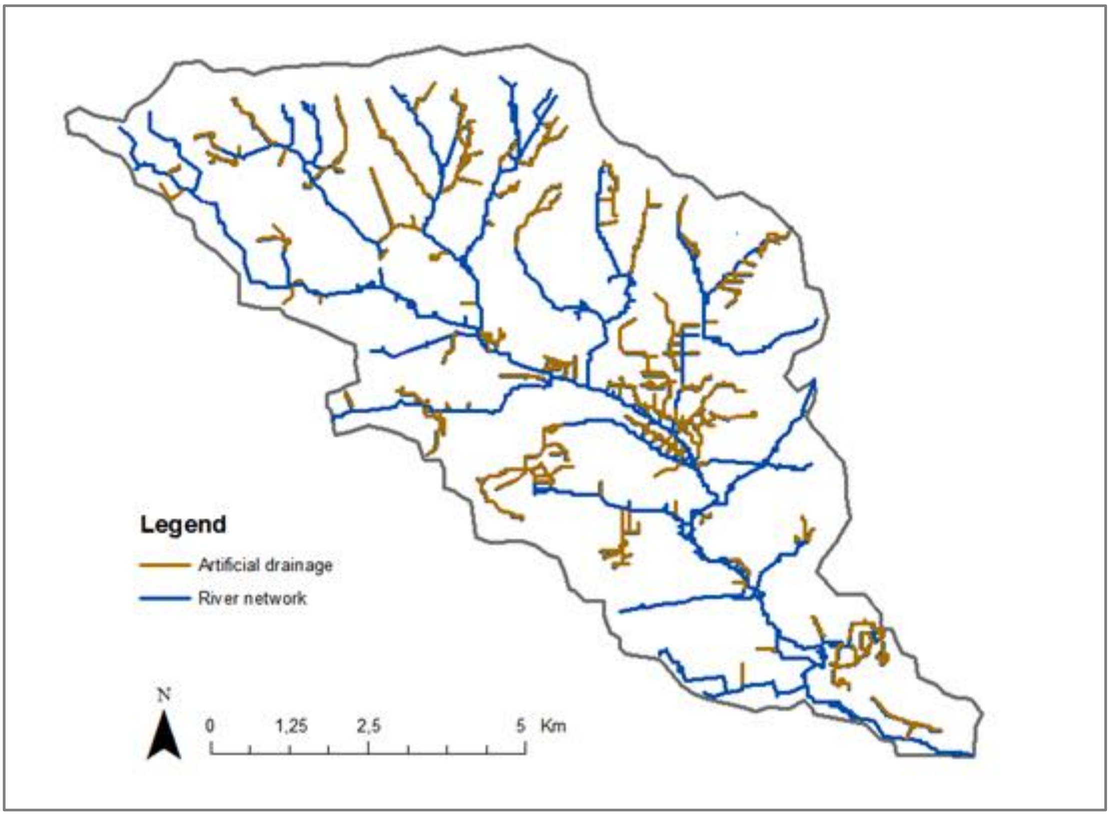

Figure 4.7. Drainage network in Tarland (digitized at James Hutton Institute)

4.7 WaSiM-ETH calibration and validation results

Model calibration and validation is the process of adjustment of the model parameters and testing the different aspects of the model to obtain a good representation of the hydrological processes and building confidence that model predictions allow for robust decision making. To calibrate and validate the model, data from the start of 2005 to the end of 2008 were utilised. As presented in Table 4.5, discharge data from 2005 were used for calibration at Coull Bridge discharge station and verified with Aboyne station data. The discharge data at Coull Bridge presented many challenges, and what had been initially expected as strong data of high hydrometric quality were in fact much less robust. In late 2006 and during 2007, a series of high flows which occurred at Coull station caused changes in channel platform and cross section. Deposition of sediments changed the hydraulic characteristics of the river channel (Sewell & Hutton, 2010). Measurements in 2008 confirmed that the river discharge at Coull Bridge was overpredicted. Thus, only data from 2006 were used for validation at this station whilst discharge measurements at Aboyne station were used for the 2006-2008 time period.

Table 4.5. Time series used for calibration and validation

	2005	2006	2007	2008
Coull Bridge	calibration	validation		
Aboyne	calibration	validation		

4.7.1 Model calibration

4.7.1.1 Calibration parameters

In the catchment there are four stations recording the water level, however only two were used for this study as discussed in Chapter 3. The Aboyne station dataset had a significant number of missing valus, so Coull Bridge station data was used for calibration. The discharge at Aboyne was used to check the goodness of fit for the calibration period, but it was not explicitly used to calibrate the model.

The main parameters used for calibrating the WaSiM-ETH model for Tarland Burn catchment are presented in Table 4.6. The model was calibrated manually and automatically using the Parameter Estimation Tool (PEST).

4.7.1.2 Manual and automatic calibration

Manual calibration

The manual calibration was undertaken by varying the parameters on a range of values. An initial calibration focussed on the main unsaturated zone module parameters, enabling a better understanding of these parameters and how they contribute to the calculation of the discharge. The main groundwater parameters (i) aquifer thickness, (ii) hydraulic conductivity in x and y axes and (iii) the leakage parameter were also manually calibrated. The calibration process for the groundwater module is described in more detail below.

Table 4.6. The most important WaSIM-ETH input data and parameters

Input		Parameter	Units	Source
Meteorological	Precipitation	Prec	mm h^{-1}	Gauged, corrected
	Temperature	Temp	^{o}C	Gauged
	Sunshine duration	Sunsh	h	Gauged
	Wind	Wind	m s^{-1}	Gauged
	Relative humidity	Humid	%	Gauged
Soil model	Storage coefficient for runoff	K_D	h	Calibrated
	Storage coefficient for interflow	Ki	h	Calibrated
	Drainage density for interflow	Dr	m^{-1}	Calibrated
	Fraction of snow melt	Sdf	-	Calibrated
Groundwater model	Aquifer thickness	Aq	m	Calibrated
	Leakage factor	Kol	s^{-1}	Calibrated
	Saturated conductivity	Kx, ky	m/s	Calibrated
Soil table	Saturated soil moisture content	Θ_{sat}	l/l	Pedo-transfer function
	Residual soil moisture content	Θ_{res}	l/l	Pedo-transfer function
	Saturated hydraulic conductivity	Ksat	m/s	Pedo-transfer function
	Van Genuchten parameter	A	-	Pedo-transfer function
	Van Genuchten parameter	N	-	Pedo-transfer function
	Recession constant for ksat for depth	Krec	-	Calibrated
Land use table	Root density	P	-	Literature
	Albedo	A	-	Literature
	Root depth	Zw	m	Literature
	Degree of vegetation coverage	V	-	Literature
	Leaf area index	LAI	l/l	Literature
	Monthly minimum surface resistance	Rsc	s/m	Literature
	Minimum suction for total evaporation	Φg	m	Literature

Automatic calibration

PEST was used for the automatic calibration of the WaSiM-ETH model. PEST is a non-linear parameter estimation software that fits model simulation with observation data by minimizing the weighted sum squared error between them (Doherty & Skahill, 2006). PEST implements a particularly robust variant of the Gauss-Marquardt-Levenberg method (damped least square method) of parameter estimation, which generally requires fewer model runs than other algorithms to solve nonlinear problems (Singh *et al*., 2012). PEST requires user specified parameter ranges and initial values for the optimisation run. The search path is along a parameter upgrade vector which is controlled by the Marquardt parameter. The optimum is reached when the difference of the objective function is within the user defined tolerance. The success of PEST estimation relies largely on the initial value of the parameters. If a point is trapped by small pits and bumps on a relatively flat objective function surface, it is not very likely for it to jump out of the trap to reach the global optimum (PEST, 2005). PEST has similar performance to other optimisation approaches such as Robust Parameter Estimateion (ROPE), however it is preferred for its lower computation demands and ease of use (Cullmann *et al*., 2006).

The parameters calibrated using PEST are noted in Table 4.7. In order to achieve a suitable rainfall and snow representation, the precipitation correction module was included in the automatic calibration with PEST. When a satisfactory representation of the meteorological parameters was achieved, the calibration focused primarily on the unsaturated zone module parameters.

Table 4.7. Parameters calibrated using PEST

Module	**Parameters**	**Description**
Precipitation correction	TO	Snow rain temperature (^{o}C)
	Ra	Correction parameter for liquid precipitation
	Rb	Correction parameter for liquid precipitation
	Sa	Correction parameter for solid precipitation
	Sb	Correction parameter for solid precipitation
Snow module	TOR	Temperature limit for rain (^{o}C)
	C0	Degree day factor
Unsaturated zone	Drd	Drainage density
	Kd	Recession constant for direct runoff
	Ki	Recession constant for interflow
	sdf	Fraction of snow melt that is direct runoff

The main unsaturated zone parameters selected for calibration are catchment specific, and are controlling the soil percolation (krec), direct runoff from snow melt (sdf), direct runoff (kd) and interflow generation (ki, dr) (Wriedt & Rode, 2006).

4.7.1.3 Land use parameters

The land cover comprises ten different broad habitats in Tarland Burn catchment, with a predominance of arable, grassland and woodland. The parameters for these land uses were defined in the WaSiM-ETH control file in the land use table. The most important parameters are presented in Table 4.8.

Table 4.8. Land use parameters

Parameters	Description
Albedo	Albedo (snow free)
LAI	Leaf area index [m2/m2]
Z0	Aerodynamic roughness length [m]
RootDepth	Root depth [m]

Default values for the land use parameters were provided in the default control file. Land use types that were similar to the land covers identified in Tarland Burn catchment were selected, and their values were verified against a literature search. The main challenge in this analysis was that most studies are measuring land use parameters for specific species of plants rather than for mixes of different species that form the vegetation for most land covers. Studies assessing these vegetation parameters in areas similar to Scotland in terms of the meteorological regime, vegetation type and soil characteristics are very limited. Notably, Breuer *et al.* (2003) calculated parameter values for the main land covers in the temperate zone by compiling 26 available land use datasets.

The albedo for different land covers has been widely investigated (Betts & Ball, 1997; Bsaibes *et al.*, 2009; Mika *et al.*, 2001) and the literature values match very well with the default values with an R^2 of 0.89 as seen in Figure 4.8.

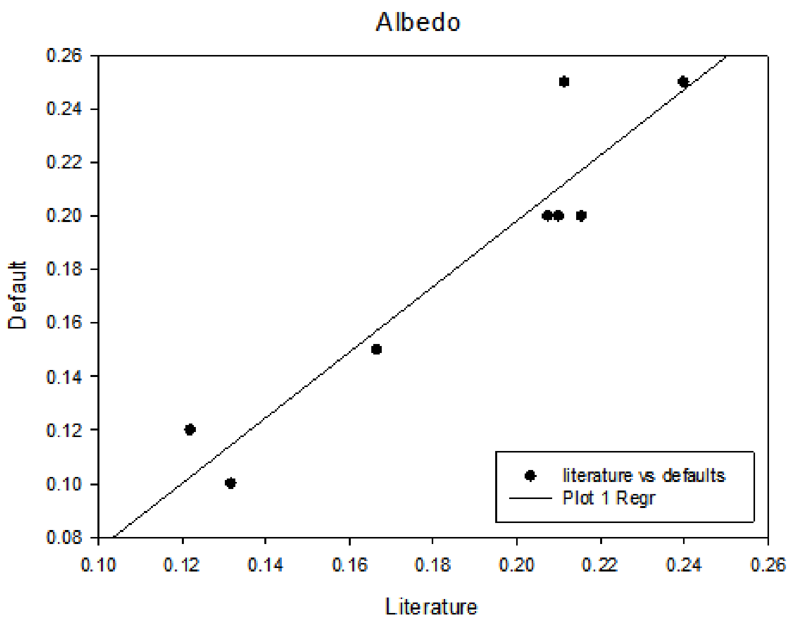

Figure 4.8. Correlation between value extracts from literature and default values for Albedo parameter

Studies measuring leaf area index (LAI) (Heiskanen *et al.*, 2011; Rautiainen *et al.*, 2009) showed a wide variability for this parameter. This was also noted by Breuer *et al.* (2003) with LAI values for coniferous forests ranging between 1.1 and 14. This may be a result of the wide variation between different coniferous trees species and planting density. The disparity in the values for this parameter is reflected in the R^2 determination coefficient which has a value of less than 0.5, with the largest differences registered for coniferous forest and dwarf shrub heath.

The aerodynamic roughness and root depth have not been investigated as widely as the parameters previously mentioned (LAI, Albedo). Studies undertaken in China (Lu *et al.*, 2003) and the Netherlands (Weligepolage *et al.*, 2012) have assessed the aerodynamic roughness of the woodland cover. A series of root depth studies have been compiled by Breuer *et al.* (2003), to reveal a wide range of values for this parameter particularly for arable and horticulture land cover. The paper notes a median value of 1.3 for root depth for arable land cover, a value comparable to that of broadleaved woodland of 1.4. With such a large degree of variability the R^2 could not be calculated for these parameters.

Conducting a literature review for vegetation parameters showed that there is large variation in values across different studies. This suggests that values from different datasets should be used with caution and indicates that there are uncertainties which should be acknowledged in assessing the results. The default values in WaSiM-ETH are within the ranges identified in the literature so they were deemed to be appropriate based on the current evidence, and used for the Tarland analysis.

4.7.1.4 Groundwater module

The most important parameters of the groundwater module were manually calibrated. Aquifer thickness and hydraulic conductivity are the main parameters dictating the groundwater flow, with the leakage playing an important role for the exfiltration into rivers. The leakage parameter recommended values were between $1e^{-5}$ and $1e^{-7}$ m/s. Lower leakage values will lead to less water exfiltrated which in turn will generate higher groundwater levels. The aquifer thickness values were based on geological information for the area, and measurements in similar catchments in Scotland (Dochartaigh *et al*., 2012).

4.7.1.5 Calibration results

Calibrating the WaSiM-ETH model for Tarland Burn catchment required sound and accurate spatial, meteorological and hydrological input data. However, as already discussed there are uncertainties associated with the discharge data both at Coull Bridge and Aboyne. Furthermore, the meteorological station is located outside of the catchment's boundaries thus failing to represent the catchment's variability in terms of rainfall. Though this is partly addressed by using correction factors (comparing the available data with the 5 km Met Office grid data, see section 3.7.1), there are many challenges in representing convective localized events. The calibration results presented graphically in Figure 4.9 and 4.10 show good results with the measured and simulated hydrographs similar and with robust diagnostic statistics presented in Table 4.9. The model seems to underestimate the peaks in January and February which could be snow on rain or rain on snow events that are typically very difficult to model (Beven, 2012). The same behaviour can be seen for the Aboyne station.

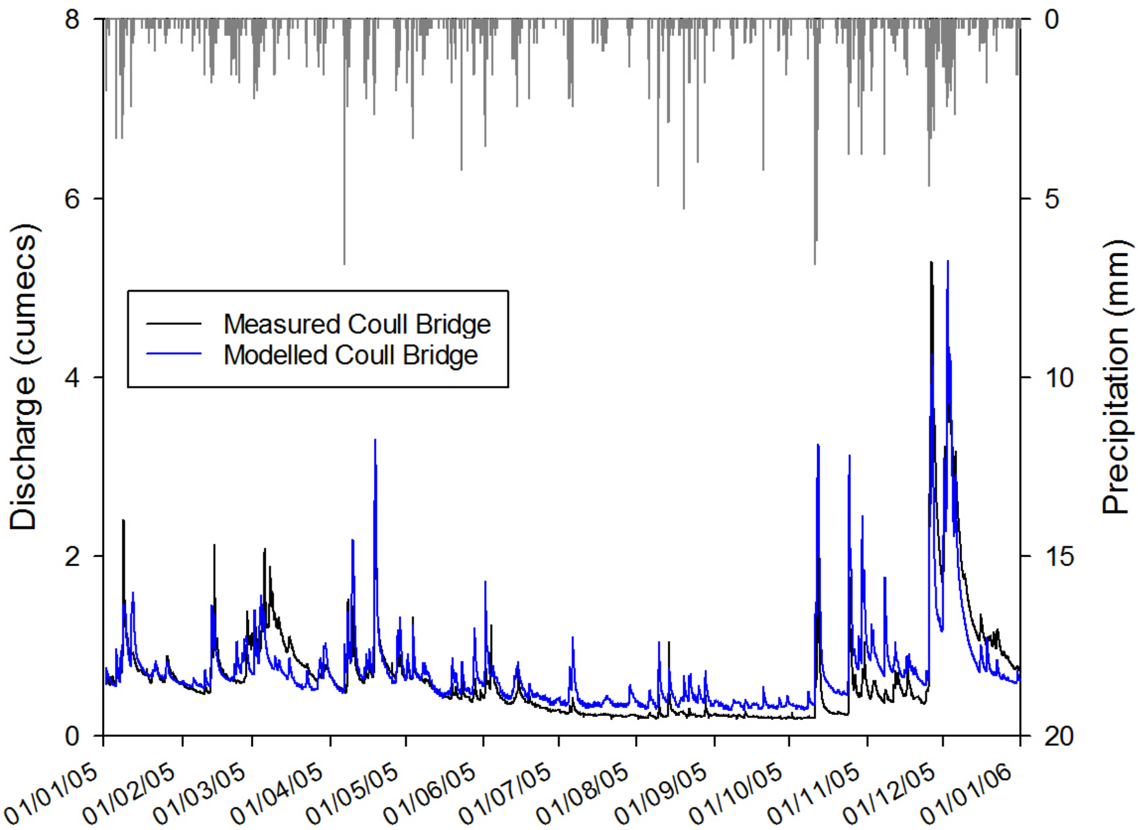

Figure 4.9. Calibration results at Coull Bridge

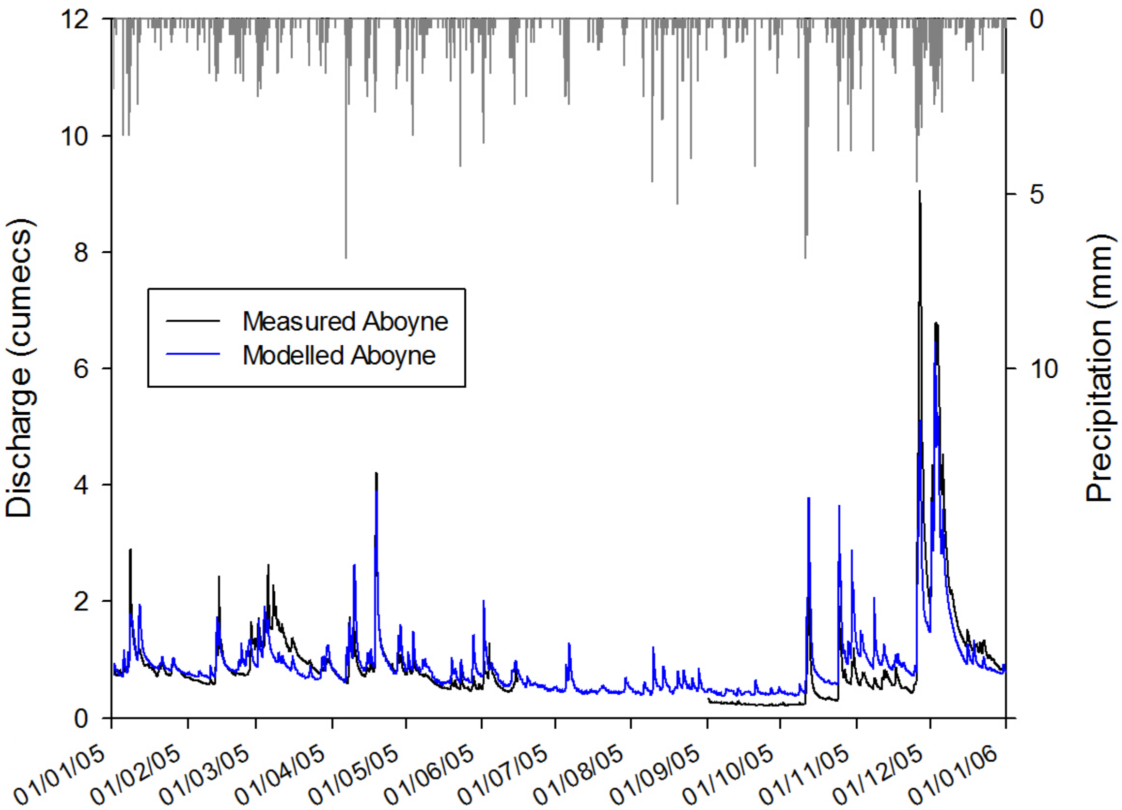

Figure 4.10. Calibration results at Aboyne station

The model is capable of capturing the seasonality effect and peak location and timings and peak magnitudes are well matched. The model seems to underestimate the peaks in the summer but has an overall good performance.

Table 4.9. Statistics for the calibration results

Calibration results	Coull Bridge	Aboyne
NSE	0.76	0.68
Logarithmic NSE	0.64	0.62
R^2	0.77	0.81
Pearson r	0.88	0.89

4.7.2 Model validation

The validation was carried out using Coull Bridge discharge for the period of January 1st 2006 to December 31st 2006. Aboyne data were used to check the results for the period of January 1st 2006 to December 1st 2008. The periods for which there were missing data at Aboyne were excluded from the efficiency coefficient's calculation.

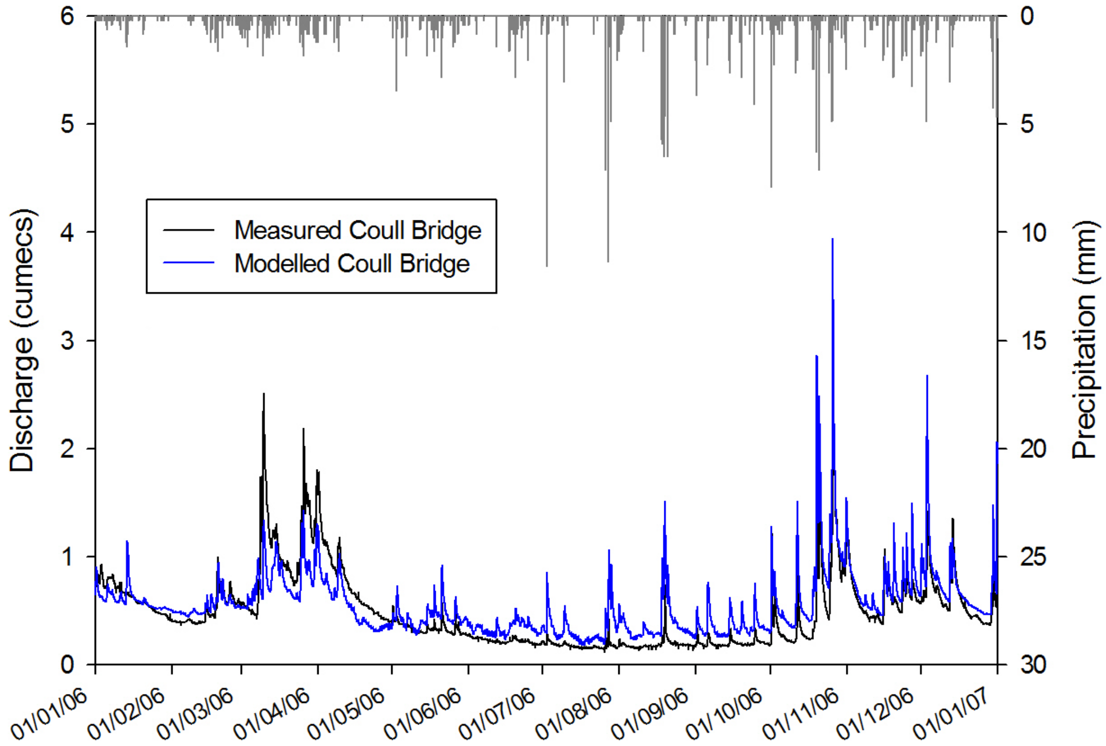

Figure 4.11. Validation results at Coull Bridge station

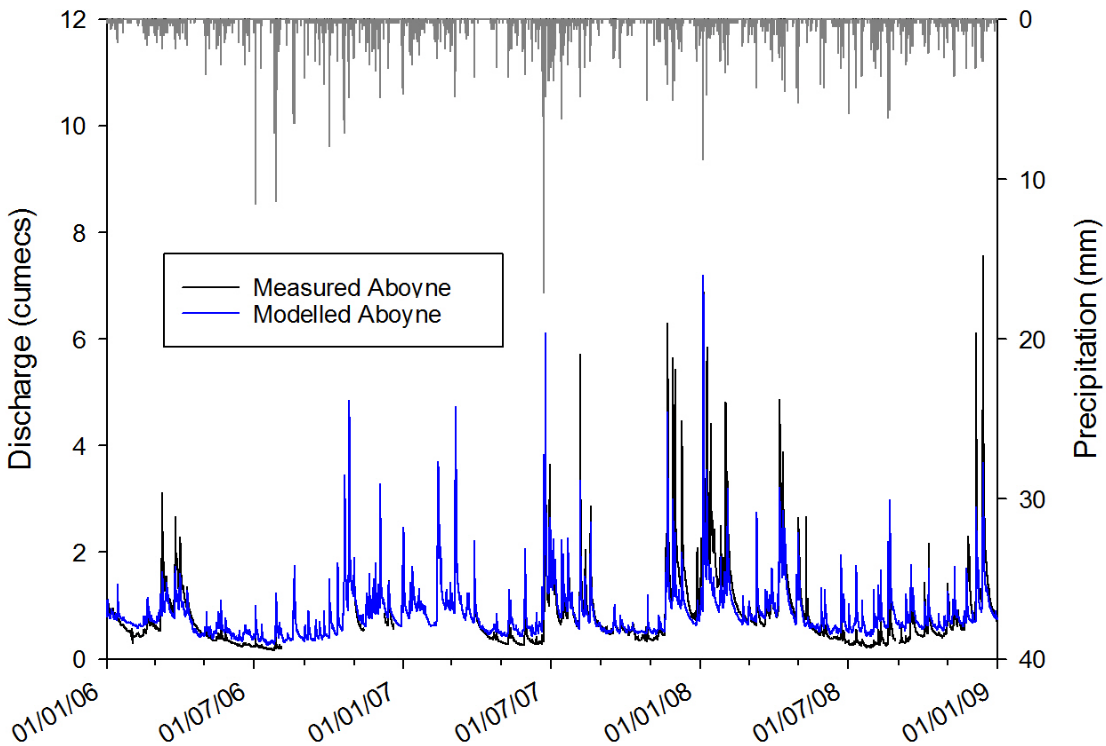

Figure 4.12. Validation at Aboyne station

The goodness of fit for the simulated and measured discharge give satisfactory efficiency coefficients with a NSE more than 0.6 and a coefficient of determination (R^2) more than 0.75 as can be seen in Table 4.10. The logarithmic NSE has a value of more than 0.71 at Coull Bridge station, which may suggest that the model performs better in simulating extremes rather than overall behaviour.

Table 4.10. Statistics for the validation results

Validation results	Coull Bridge	Aboyne
NSE	0.63	0.6
Logarithmic NSE	0.71	0.64
R^2	0.76	0.75
Pearson r	0.81	0.87

4.7.3 Model uncertainty

The way in which uncertainty factors impact on the hydrological models can be observed through the model response during the calibration phase. The study of Wriedt ad Rode (2006) investigated parameter uncertainty for WaSiM-ETH based on a DYNIA uncertainty framework which uses a Monte-Carlo Simulation (Wagener *et al.*, 2003). The study provided a probability distribution function (pdf) and cumulative pdf for the main parameters controlling the runoff generation. The results showed that the pdf for Kd and Ki is less defined, suggesting higher uncertainty levels for these parameters. The authors noted a relationship between the Drd and discharge which could be a result of the indirect effect of interflow generation (which relates to soil moisture, catchment wetness and antecedent rainfall) and observed discharge. It could also suggest that for higher discharge, interflow processes become less important (Wriedt & Rode, 2006). Another study by Gädeke *et al*. (2013) investigated the uncertainties related to the choice of the hydrological model in a climate assessment study for a German catchment. The study compared WaSiM-ETH with HBV-light lumped model and noted the robustness of WaSiM-ETH, as the physical basis is maintaining the system dynamic beyond calibration period. Moreover for climate change investigations Najafi *et al*. (2011) suggested that uncertainty associated with the hydrological model is much lower when compared to climate input uncertainty, supported by Prudhomme *et al*. (2010). The model is used for the Tarland research to assess the relative change related to the implementation of NFM options under the current and future climate rather than an absolute value. Whilst sources of uncertainties are acknowledged, a full uncertainty analysis was not undertaken as it was beyond the scope of the study.

4.8 Summary

WaSiM-ETH is a fully distributed model that uses physically based algorithms to describe most of the processes relevant for runoff generation. The model allows a representation of the spatial distribution of catchment characteristics and is based on spatial and temporal dynamics of climatic variables (Schulla & Jasper, 2000).

The WaSiM-ETH model can separate the flow into all three components: baseflow, interflow and surface runoff. Baseflow separation is regarded as groundwater exfiltration into the surface river system for defined river grid-cells. Groundwater can be represented either by using an integrated two-dimensional groundwater model or using a simplistic conceptual linear storage approach defined by two parameters. Though the latter is often used when applying WaSiM-ETH (Hölzel *et al.*, 2011, Rössler *et al.*, 2012) mainly in alpine catchments, this approach is not deemed suitable in lowlands where groundwater storage plays an important role in the water balance. Richard equations are used to calculate the water fluxes in the unsaturated zone using van Genuchten parameters. Interflow is calculated using the Green and Ampt (1911) approach and saturation time is computed using the Peschke (1987) equation. Surface runoff is generated for each grid cell by including the infiltration excess and saturation overland flow. A single reservoir cascade approach (isochronic approach with additional retention) is used for both surface runoff and interflow. The total runoff is then computed by summing up the average value for each runoff component which constitutes the input to the routing model; the total discharge is routed through predefined routing sections using a kinematic wave approach based on flow velocity of the Manning–Strickler equation (Manning, 1890; Strickler, 1923)**.**

The calibration was undertaken using discharge measurements at Coull Bridge verified against discharge measurement at Aboyne station for the 1^{st} of January 2005 to 31^{st} of December 2005 time period. The calibration was carried out manually and automatically using PEST software. Several challenges have been identified and addressed in the calibration phase. High flows at the Coull Bridge station in late 2006 and at the beginning of 2007 have generated changes in the river channel leading to overestimation. Therefore only 2006 discharge data were used for validation at Coull Bridge, and at Aboyne station discharge data for the 2006 to 2008 time period were used. The calibration and validation results showed a good fit between the observed and the modelled discharge, providing good levels of confidence in using the model for the purposes of this investigation.

Chapter 5. The impact of climate change in Tarland for the current land use

5.1 Introduction

Scotland has in general good long-term records of changes in climate, though with some variability across the different climatic variables. Temperature has increased by an annual average of 1 ^{o}C since 1960 across the three regions (North, West, East) as defined by the UKCP09 (Werritty & Sugden, 2013). Annual precipitation has risen by an average of 21.1% since 1961 through to 2004 and the frequency and magnitude of extreme weather events has increased (Barnett *et al.*, 2006).

These trends are expected to continue in the future, according to the scientific consensus of climate change science (IPCC, 2014c). The UKCP09 Climate Projections provide estimates of change for a number of climate parameters over 30-year time periods (Murphy *et al.*, 2009). The projections explicitly include uncertainties by generating projections within the estimated probabilities of different outcomes from a multi-model ensemble rather than providing a deterministic output. Drawn from the UKCP09, the Weather Generator produces synthetic time series at an hourly and daily time scale, accounting for local topographic information at a 5 km scale (Jones *et al.*, 2009).

To understand how the extreme rainfall events are expected to change in the future for Tarland, an extreme value analysis of the climate projections was undertaken. The extreme rainfall events of 10-year and 100-year return periods were inputted in the WaSiM-ETH model calibrated for the Tarland catchment, and the changes in discharge assessed. The results are presented in this chapter with a consideration for the changes in the extreme rainfall patterns and discharge response.

5.2 Methodology

Weather Generator outputs based on the UKCP09 climate downscaling tool have been used for this project. The UKCP09 Weather Generator (Jones *et al.*, 2009) provides climate projections centred on the 2020s, 2050s and 2080s. One hundred Weather Generator outputs were downloaded for each time slice which is the recommended number to preserve the statistical behaviour of the climate projections (Jones *et al.*, 2009). For computational considerations the medium emission scenario (IPCC A1B) was used for the project, as the major differences in climate up to the 2050 is mainly influenced by the earth system parameters used to run climate models in the ensemble rather than greenhouse gas emissions (Murphy *et al*., 2009). The central estimate is more reliable than the high and the low emission scenarios due to constraints posed by the experimental design (e.g. a discrepancy term for future projected variables is assumed to be the same for all three emission scenarios as those obtained using A1B1). The data were downloaded for hourly time steps for the 5 km grid, which included Tarland located in the centre of the catchment with the latitude: 57.1249 and longitude -2.8575 as seen in Figure 5.1.

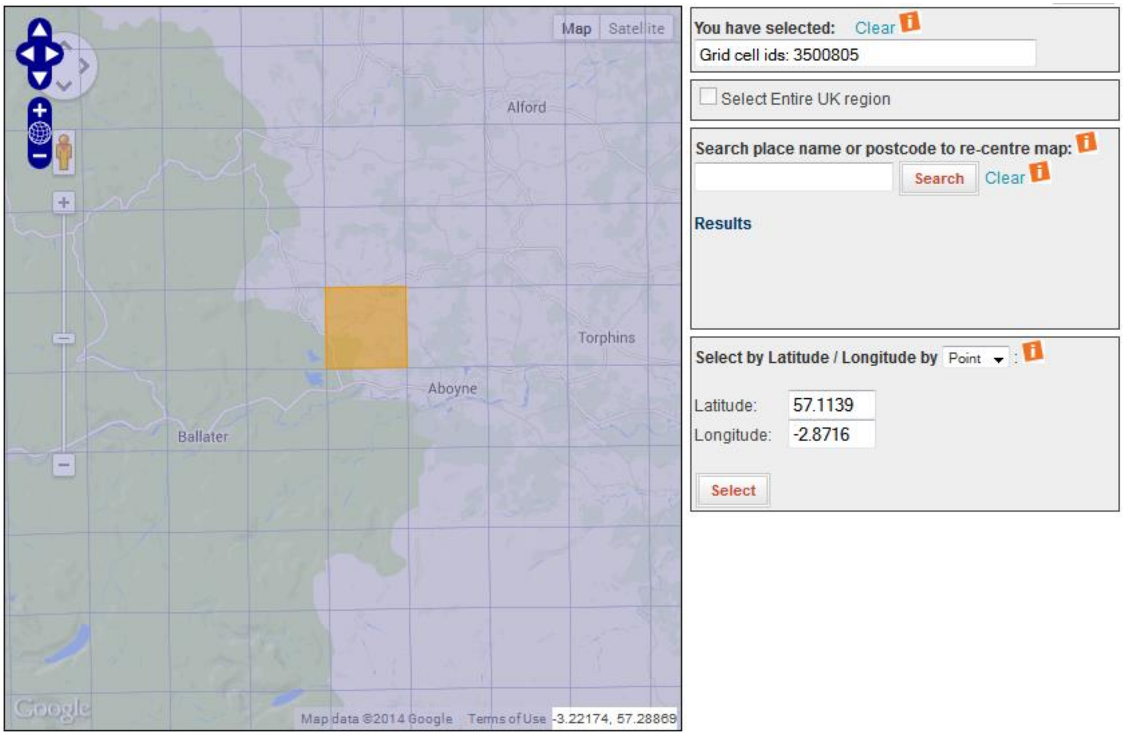

Figure 5.1. Coordinates of the selected point for the Weather Generator data download

The parameters downloaded from the Weather Generator were precipitation, relative humidity, temperature and sunshine (Table 5.1). The wind parameter is not provided in the Weather Generator outputs as its uncertainty was considered to be too high. For the project, a simplistic approach was used to calculate an hourly average from the measured wind data at Aboyne from 2004 to 2009.

Table 5.1. Downloaded data from the Weather Generator

Name	2020s	2050s	2080s
Time period	2010-2039	2040-2069	2040-2069
Parameters	Precipitation		
	Relative Humidity		
	Temperature		
	Sunshine		
Probability level	Medium		
Time step	Hourly		

One hundred rainfall outputs were downloaded from the Weather Generator for each time frame: 2020s, 2050s and 2080s for the medium emission scenario, representing the conditions up to the end of the current century. The results of the climate projections analysis were referenced against the baseline synthetic data for 1961-1990. Baseline meteorological data were downloaded from the Weather Generator containing 30 years of hourly data. Precipitation data were extracted and the annual maxima (AM) were calculated for 7 hour and 15 hour events. The choice of the 7 hour duration was informed by the design duration identified for Tarland Burn catchment using the REFH approach, calculated according to Equation (5.1). The 15 hour duration was selected to capture events of longer duration.

$$D = T_p\left(1 + \frac{SAAR}{1000}\right) \qquad (5.1)$$

The probability distribution for extreme flood events was calculated using the L-moments fitting technique for General Extreme Values. The L-moments technique gives a more robust fit than the product moments technique (Svensson & Jones, 2010) and has been previously used for regional frequency analysis in United Kingdom (Fowler & Kilsby, 2003). Most methods for rainfall frequency estimation rely on the analysis of the Annual Maxima (AM) series, though the peak over threshold (POT) method is theoretically recommended (Fowler & Kilsby, 2003). The POT includes all large events and it excludes the AM which could be misleading in an extreme value analysis if such values are low; however, manually selecting which peaks to exclude can be very time consuming (Fowler & Kilsby, 2003). The POT method was noted to generate better results than the AM method, however the difference between the two methods is only important at short return periods of less than 5-10 years (Madsen *et al*., 1997). As this project seeks to investigate events beyond the 10 year return period, the AM method was deemed fit for the purpose.

The total rainfall for 2-year up to 1000-year return period events were generated. For investigations of the impact on the discharge, the 10-year and 100-year events were selected as representing the indices most commonly used in hydrological studies validated against the FEH estimates (Institute Hydrology, 1999). The extreme rainfall events need to be distributed in an hourly time step, as required by the WaSiM-ETH model. The FEH method has been widely used in hydrological studies (Black & Burns, 2002; Fowler & Kilsby, 2003; Fowler *et al*., 2005) generating symmetric and single peaked design storm profiles (Kjeldsen, 2007). The model for the design profiles, initially developed for the FSR method, was included in the Micro-FSR software. The proportional depth of rain (y) falling in a temporal proportion (x) of the total duration is calculated according to Equation 5.2.

$$y = \frac{1 - a^z}{1 - a} \qquad (5.2)$$

Where z=xb, a and b are profile specific constants.

Two rainfall profiles are available - 50% summer and 75% winter – for the FEH method which were adopted for the modelling exercise. The 50% summer profile, recommended for urbanised catchments, is on average more peaked than 50% of the observed UK summer storms, whilst the 75% winter recommended for rural catchments, is on average more peaked than 75% of observed UK winter storms (Kjeldsen, 2007). The 50% profile is more peaked than the 75% profile due to the convective rainfall occurring in the summer. The method has been reviewed by Faulkner (1999) who notes that the imposed symmetry and peaked profiles make it unsuitable for large catchments where the critical rainfall duration can be more than 7 days. However this is not the case for Tarland Burn catchment, so the FEH method was deemed a good choice for the redistribution of rainfall.

The extreme rainfall events were inputted to the WaSiM-ETH for summer and winter antecedent conditions, to investigate how they would impact on the discharge during wet and dry conditions. The WaSiM-ETH model was then trained using summer and winter meteorological data for the period of 1st of January 2004 to 30th of June 2009. The summer period includes June, July and August months; the winter period comprises of November, December and January months. The model was applied using a 9 month spin-up period, keeping the rest of the model and meteorological parameters constant. The distributions for summer and winter events for the baseline, 2020s, 2050s and

2080s across the two selected event durations (7 hour and 15 hour) and event magnitudes (10-year and 100-year return period) are provided in Appendix C.

5.3 Climate trends in the east of Scotland and future climate

Scotland's climate has been subject to recent latitudinal warming trends and changes in rainfall. The pattern of Scottish regional temperature change has broadly followed global trends, gradually increasing throughout the first half of the century, followed by a decrease during the 1950s and 1960s before steadily increasing towards the end of the century (Figure 5.2). The Eastern side of Scotland has seen the mean annual temperature rise from approximately 6.6 ^{o}C to 7.5 ^{o}C, which is slightly less than the West of Scotland, the mildest of the three regions (North, East, West) (Barnett *et al*., 2006b).

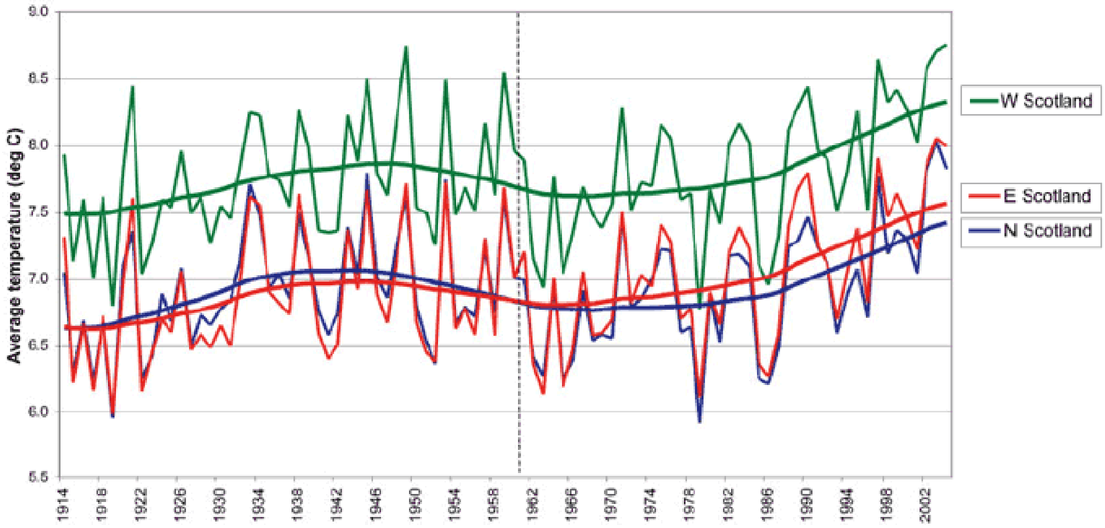

Figure 5.2. The annual average temperature (in ^{o}C) for the North, East and West of Scotland from 1914 to 2004, with smoothed curves showing a running average across the record. The vertical dashed line marks 1961 (Barnett et al. 2006a)

Scotland's rainfall is spatially extremely variable with the annual totals differing between a maximum of 3000 mm in the west, at high altitude, to 500-800 mm in the lowland south and east (Werritty & Sugden, 2013). The most notable recent trend has been an increase in winter rainfall for all three regions, an average of 58.3% change. Though the Eastern side of Scotland has seen the smallest change in average rainfall totals for the winter during 1961-2004 (36.5%), it has experienced the highest increase during the autumn, with a change in the average rainfall totals of 22.2% (see Table 5.2). The Highlands provide a rain shadow effect for the Eastern side of Scotland because westerly winds predominate, causing the North and the West of Scotland to receive more rainfall than the East (Werritty & Sugden, 2013). This effect is clearly seen in the climatology of the Tarland Burn catchment, as already discussed in Chapter 3.

Table 5.2. Changes in average precipitation totals as % between 1961-2004 (Barnett *et al.*, 2006b)

	1961-2004			
	East Scotland	West Scotland	North Scotland	Scotland
Spring	9.4	17.3	16.2	14.8
Summer	0.2	7.3	-7	-0.6
Autumn	22.2	5.9	5.3	9.1
Winter	36.5	61.3	68.9	58.3
Annual	18.4	23.3	21	21.1

The increasing trends are less well established aver an extended 1914-2004 period, as evidenced by Barnett *et al.* (2006a) highlighting the short-comings of a short time series. The difference is caused by a lower inter-annual variability during the 1960s-1970s period, followed by a wet period (Barnett *et al.*, 2006b). Whilst the ambiguities in long term trends do not undermine the more established trends for the 1961-2004 period, they do emphasise the need to be clear in specifying appropriate probability levels and acknowledging that the derivation and attribution of trends needs to be applied cautiously (Werritty & Sugden, 2013).

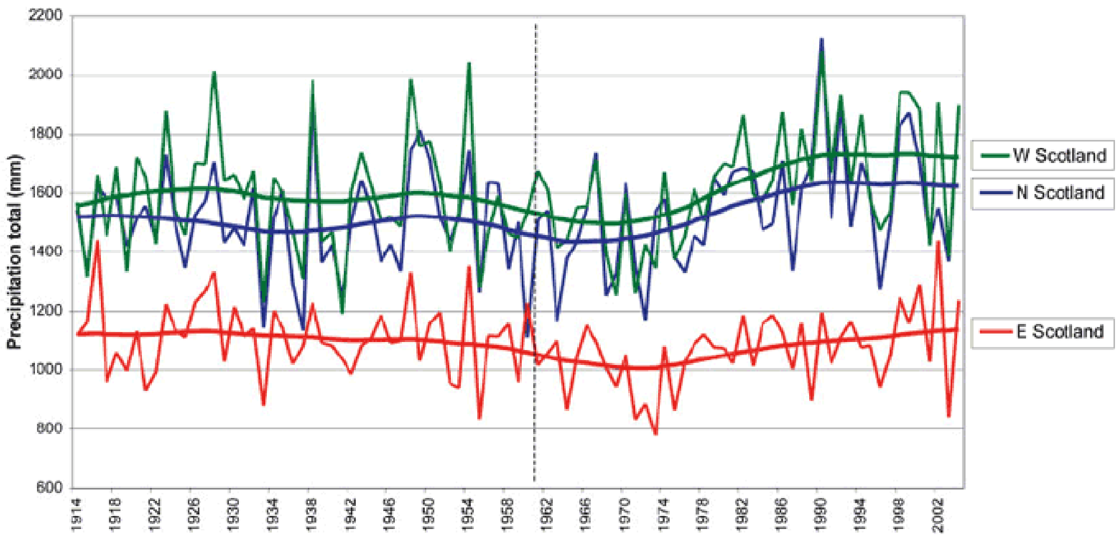

Figure 5.3. Precipitation total (in mm) for North, East and West of Scotland from 1914 to 2004, with smoothed curves to show a running average across the record. The vertical dashed line marks 1961 (Barnett *et al*., 2006)

The UKCP09 climate trends project confirmed the short-term trends in Scottish rainfall since 1961 (Jenkins *et al*., 2009). With regard to the future, the UKCP09 Climate Projections project warmer and drier summers, and warmer and wetter winters with an increased frequency of extreme weather events (Murphy *et al*., 2009). For the east of

Scotland, an average temperature increase of 2.3 ^{o}C for the summer and 1.7 ^{o}C for the winter is predicted under the medium emission scenario for the 2050s. The precipitation is expected to decrease in the summer by an average of 13%, whilst it is predicted to increase in the winter by approximately 10% (Murphy *et al*., 2009).

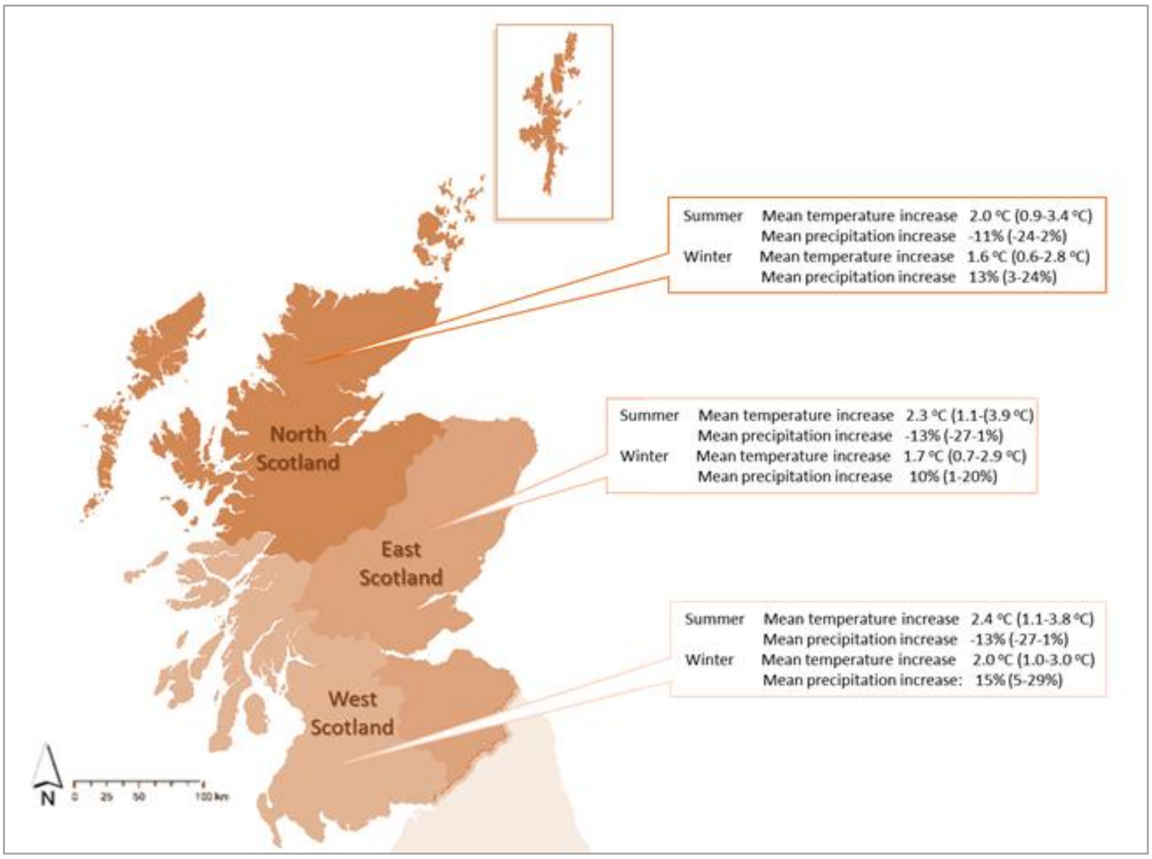

Figure 5.4. Mean temperature and precipitation increase in Scotland in 2050s under the medium emissions scenario. For each region the middle point of the probability range is presented along with the range within which the actual change is likely to be in brackets (adapted from Murphy et al., 2009)

The UKCP09 Weather Generator is capable of providing plausible realisations of hourly and daily time series, for the main meteorological parameters both for the future and for the 1961-1990 baseline. The Weather Generator provides a synthetic hourly time series of temperature (mean, maximum and minimum), precipitation, vapour pressure, relative humidity, sunshine and potential evapotranspiration (PET) at a 5 km resolution. Whilst the Weather Generator does not append additional climate change information to the 25 km projections, it adds local topographic information at the 5 km scale, as it is based on observed data which is representative of this smaller scale (Jones *et al*., 2009).

5.4 Climate projections for Tarland catchment

The frequency of extreme rainfall weather events is expected to increase with impacts disproportionate to their increasing frequency (Werritty & Sugden, 2013). Figures 5.5 and 5.6 present the climate projections for the baseline, 2020s, 2050s and 2080s time slices across a wide range of event magnitudes for 7 hour duration events and 15 hour duration events, respectively. The analysis demonstrates an increase in precipitation in the Tarland catchment for the future climate. Heavier rainfall is expected across all event magnitudes from the 2-year return period to the 1000-year return period.

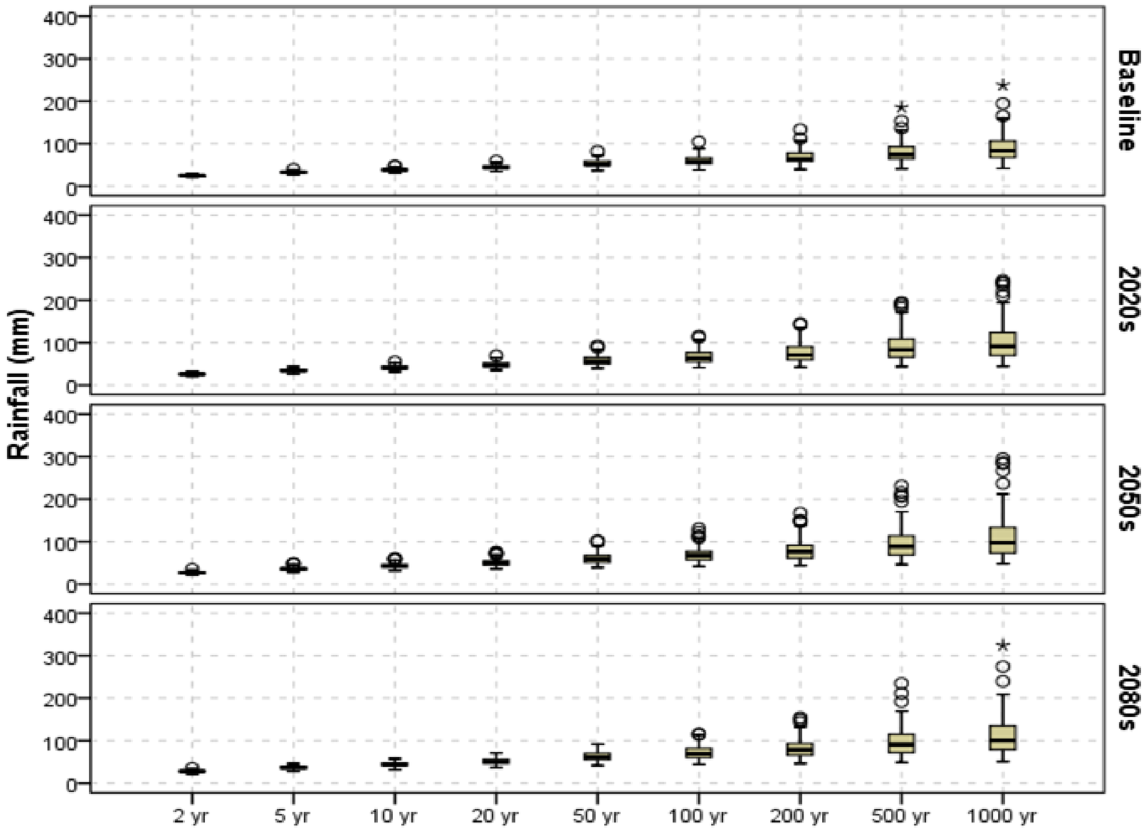

Figure 5.5. Climate projections for the baseline (1961-1990) and the medium emissions scenario for 2020s, 2050s and 2080s for 7 hour event duration

Across the different rainfall event magnitudes, the level of uncertainty increases for larger events, as the values are spread on a wider interval, and there is an increase in the number and spread of outliers.

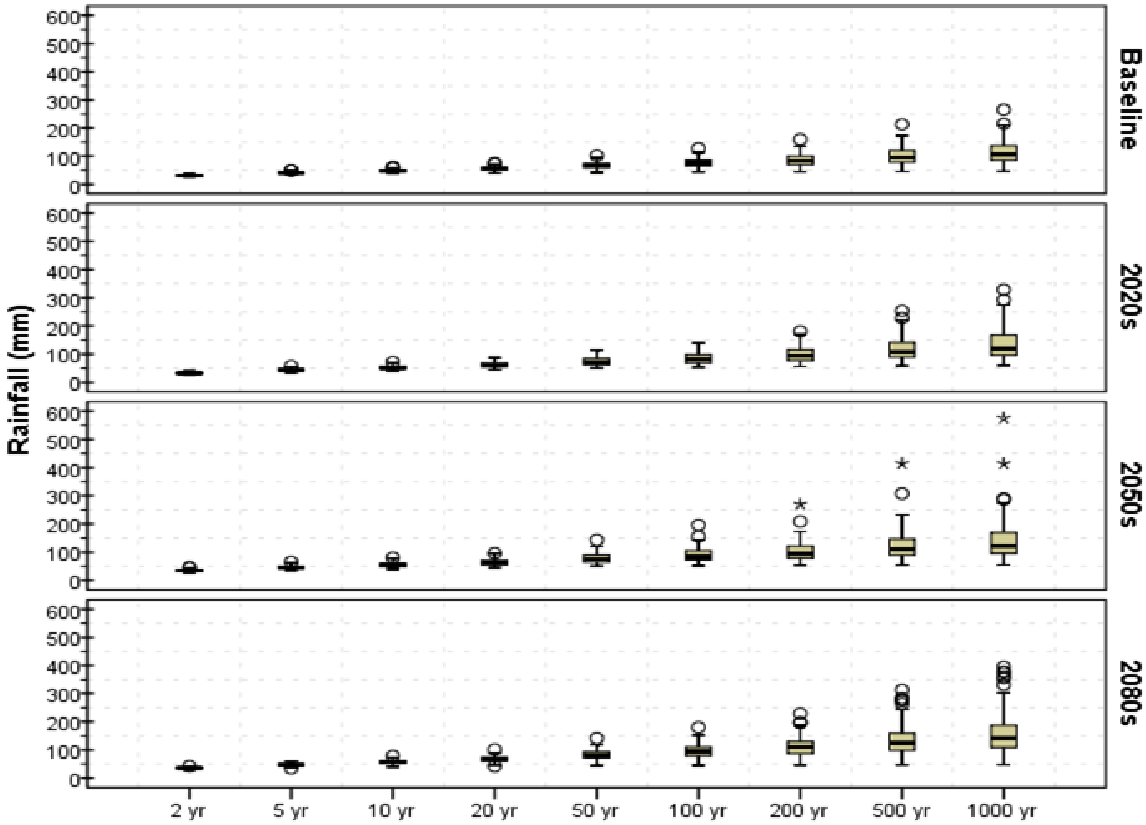

Figure 5.6. Climate projections for the baseline (1961-1990) and the medium emissions scenario for 2020s, 2050s and 2080s for 15 hour event duration

Table 5.3 presents the mean and the standard deviation for the baseline and the three climate projection datasets (2020s, 2050s and 2080s), after the extreme value analysis. It can be seen that the standard deviation is rising as the extreme rainfall event magnitude increases, which suggests that the range of data are more dispersed at the high end of the spectrum.

Table 5.3. The mean and standard deviation for the rainfall baseline (1961-1990), 2020s, 2050s and 2080s under the medium emissions scenario

Return period (years)	Rainfall (mm)	Baseline		2020s		2050s		2080s	
		Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
2	**7 hour**	24.9	1.6	26.2	2.1	27.1	2.9	27.9	2.4
	15 hour	30.9	2.2	32.8	2.9	34.4	4	35.5	3
5	**7 hour**	32.8	2.5	35	3.4	36.4	4.5	37.2	3.8
	15 hour	40.9	3.5	44.2	4.8	46.5	6.3	47.9	5.1
10	**7 hour**	38.6	3.4	41.4	4.9	43.3	6	44.2	5.1
	15 hour	48.2	4.8	52.6	6.6	55.4	8.4	57.4	7.1
20	**7 hour**	44.6	4.9	48.2	7.1	50.7	8.2	51.6	7.1
	15 hour	55.9	6.7	61.6	9.3	64.9	11.5	67.6	10.1
50	**7 hour**	53.3	8.1	58.2	11.5	61.6	12.9	62.5	11.2

	15 hour	67	10.5	74.7	14.5	78.8	18	83	16.5
100	**7 hour**	60.6	11.6	66.8	16.4	71	18.2	71.8	16
	15 hour	76.4	14.7	85.9	20.2	90.9	25.4	96.6	23.9
200	**7 hour**	68.7	16.4	76.4	22.9	81.7	25.4	82.5	22.7
	15 hour	86.9	20.3	98.6	27.9	104.6	35.7	112.4	34.3
500	**7 hour**	81	25	91.2	34.9	98.4	38.9	98.9	35.3
	15 hour	102.7	30.4	117.9	41.8	125.9	55.7	137.6	54.3
1000	**7 hour**	91.7	33.7	104.8	47.2	113.4	53.2	113.6	48.7
	15 hour	116.5	40.7	135.1	56.1	145.2	77.4	160.8	76.1

Table 5.4 provides the 10-year and 100-year return period, for the 7 hour and 15 hour event durations, for the baseline and the 2020s climate projection, for the medium emission scenario. Table 5.5 and Table 5.6 present the equivalent data for the 2050s and 2080s respectively. The observed values in these tables are taken from the depth-duration-frequency rainfall statistics provided by the Flood Estimation Handbook (Institute Hydrology, 1999). They provide the currently accepted value based on the analysis of the observed data (in mm). There is a high level of agreement between the 'observed' and the baseline values from the Weather Generator, which gives confidence that the data from the Weather Generator are able to robustly predict the rainfall parameters.

Table 5.4. 10-year and 100-year return period rainfall for 7 hour and 15 hour event durations derived from the Weather Generator for the baseline and 2020s

Event duration	**Return period**	**Observed (FEH)**	**Baseline 1961-1990**				**2020s**			
			10th %tile	50th %tile	90th %tile	MEAN	10th %tile	50th %tile	90th %tile	MEAN
7 hour event	10	**35.10**	34.42	38.62	43.01	38.57	35.58	40.21	48.39	41.43
	100	**55.49**	48.01	57.22	76.59	60.57	48.46	63.41	91.73	66.75
15 hour event	10	**49.53**	41.73	47.88	55.18	48.19	44.71	51.39	62.22	52.64
	100	**76.23**	59.85	74.68	95.39	76.43	63.67	82.17	116.16	85.92

Table 5.5. 10-year and 100-year return period rainfall for 7 hour and 15 hour event durations derived from the Weather Generator for the baseline and 2050s

Event duration	**Return period**	**Observed (FEH)**	**Baseline 1961-1990**				**2050s**			
			10th %tile	50th %tile	90th %tile	MEAN	10th %tile	50th %tile	90th %tile	MEAN
7 hour event	10	**35.10**	34.42	38.62	43.01	38.57	36.38	42.61	50.72	43.30
	100	**55.49**	48.01	57.22	76.59	60.57	50.56	67.68	98.15	70.98
15 hour event	10	**49.53**	41.73	47.88	55.18	48.19	45.65	55.42	67.39	55.39
	100	**76.23**	59.85	74.68	95.39	76.43	62.83	84.92	128.2	90.88

Table 5.6. 10-year and 100-year return period rainfall for 7 hour and 15 hour event durations derived from the Weather Generator for the baseline and 2080s

Event duration	Return period	Observed (FEH)	Baseline 1961-1990				2080s			
			10th %tile	50th %tile	90th %tile	MEAN	10th %tile	50th %tile	90th %tile	MEAN
7 hour event	10	**35.10**	34.42	38.62	43.01	38.57	37.34	43.70	51.19	44.20
	100	**55.49**	48.01	57.22	76.59	60.57	51.39	69.77	94.79	71.84
15 hour event	10	**49.53**	41.73	47.88	55.18	48.19	48.77	57.35	67.03	57.39
	100	**76.23**	59.85	74.68	95.39	76.43	68.84	95.09	129.40	96.64

The mean is slightly higher than the median (the 50 percentile) as it can be influenced by large values at the top end of the distribution, which the median is designed to exclude. However in this case there is not a significant difference between the mean and the median, as the Weather Generator is only influenced by 30 years of data used to define the statistical relationships, thereby producing a tendency to generate conservative results rather than extreme outliers (Kilsby *et al*., 2007). For this reason, the Weather Generator outputs will generally not produce very large values and the extremes are typically similar in each run. Given that the mean fitted the observed data better overall, it was adopted for the discharge analysis.

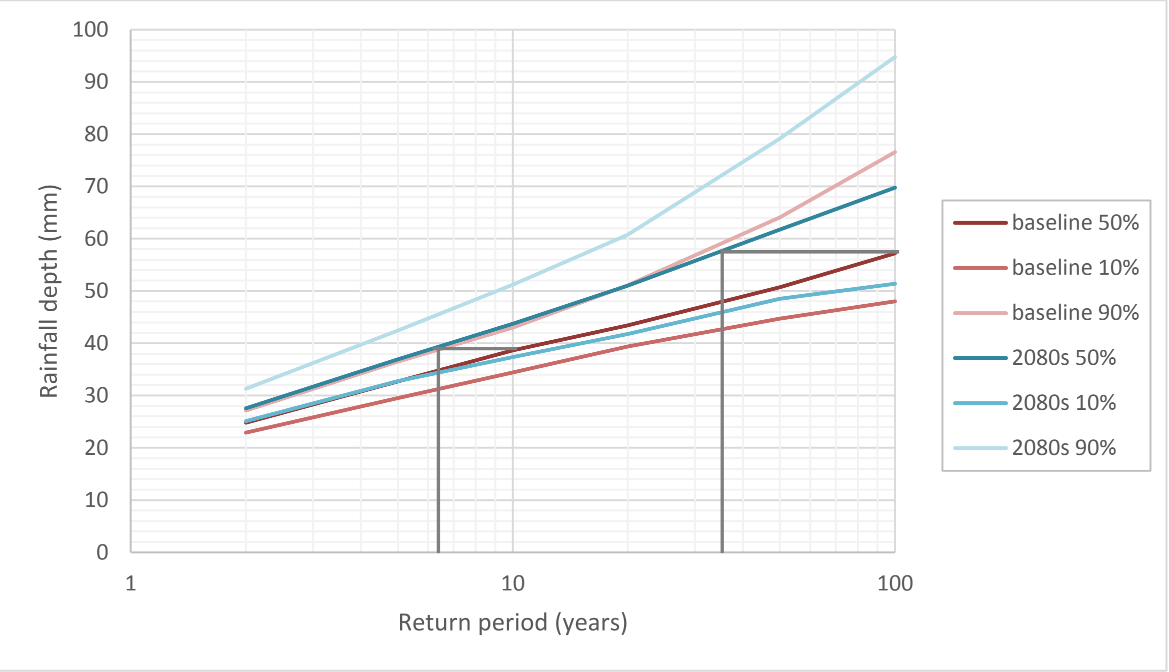

Figure 5.7. Appraisal of the frequency of the baseline 10-year and 100-year rainfall events (for 7 hour event duration) by the 2080s for the medium emission scenario

The change in the frequency of rainfall events from 2-year up to a 100-year period was estimated for 7 hour events for the 2080s medium emission scenario (Figure 5.7). The return period is shown on the x axis in a logarithmic scale. For the Tarland catchment, the baseline 100-year rainfall event is estimated to become a 38-year rainfall event in

2080s. The baseline 1 in 10 year rainfall event is estimated to become as frequent as a 1 in 6 year event by the 2080s.

5.5 Assessing the changes in discharge for future climate in Tarland catchment

The results suggest a significant shift in the peak flow for future climate projections (Table 5.7, Figures 5.8 and 5.9). The changes are more pronounced for the higher return period (i.e. 100 year return period) and for the 15 hour event duration. A maximum discharge of c. 16 m^3s^{-1} could be generated if the 100 year return period event occurred in the winter (the 2080s climate projections) for both event durations: 7 hour and 15 hour).

Table 5.7.The flow peaks (m^3s^{-1}) for 10 years and 100 years return period events if they occurred in the summer and in the winter for the baseline (1961-1990) and 2020s, 2050s and 2080s (medium emissions scenario)

	Summer 10 year return period		**Summer 100 year return period**		**Winter 10 year return period**		**Winter 100 year return period**	
	7 hour	15 hour	7 hour	15 hour	7 hour	15 hour	7 hour	15 hour
Baseline	3.39	4.33	5.99	8.35	7.07	8.53	12.54	12.60
2020s	3.68	4.85	6.84	10.05	7.75	9.09	14.29	13.98
2050s	3.88	5.19	7.46	11.01	8.17	9.44	15.61	14.70
2080s	3.97	5.44	7.58	12.14	8.38	9.71	15.88	15.59

The flow peaks are expected to increase between 6.5% and 45% for the future climate (depending on the type of event), compared to the 1961-1990 baseline (Table 5.8). The 15 hour 100-year return period events could generate an increase in the peaks by up to 20% for the 2020s, by up to 31.8% for the 2050s and by up to 45% more by the 2080s, if the extreme event occurred in the winter. Thus what is currently a 1 in 12 year flood event could increase in magnitude to that currently occurring as a 1 in 25 year event by the 2050s and a 1 in 33 year event by 2080s (cf. Figure 3.17). The changes in the peak could be more pronounced for low duration events (i.e. 7 hour). For extreme events occurring in the winter, the discharge could increase by 25% by the 2050s and by 27% by the 2080s (for 100-year return period rainfall events).

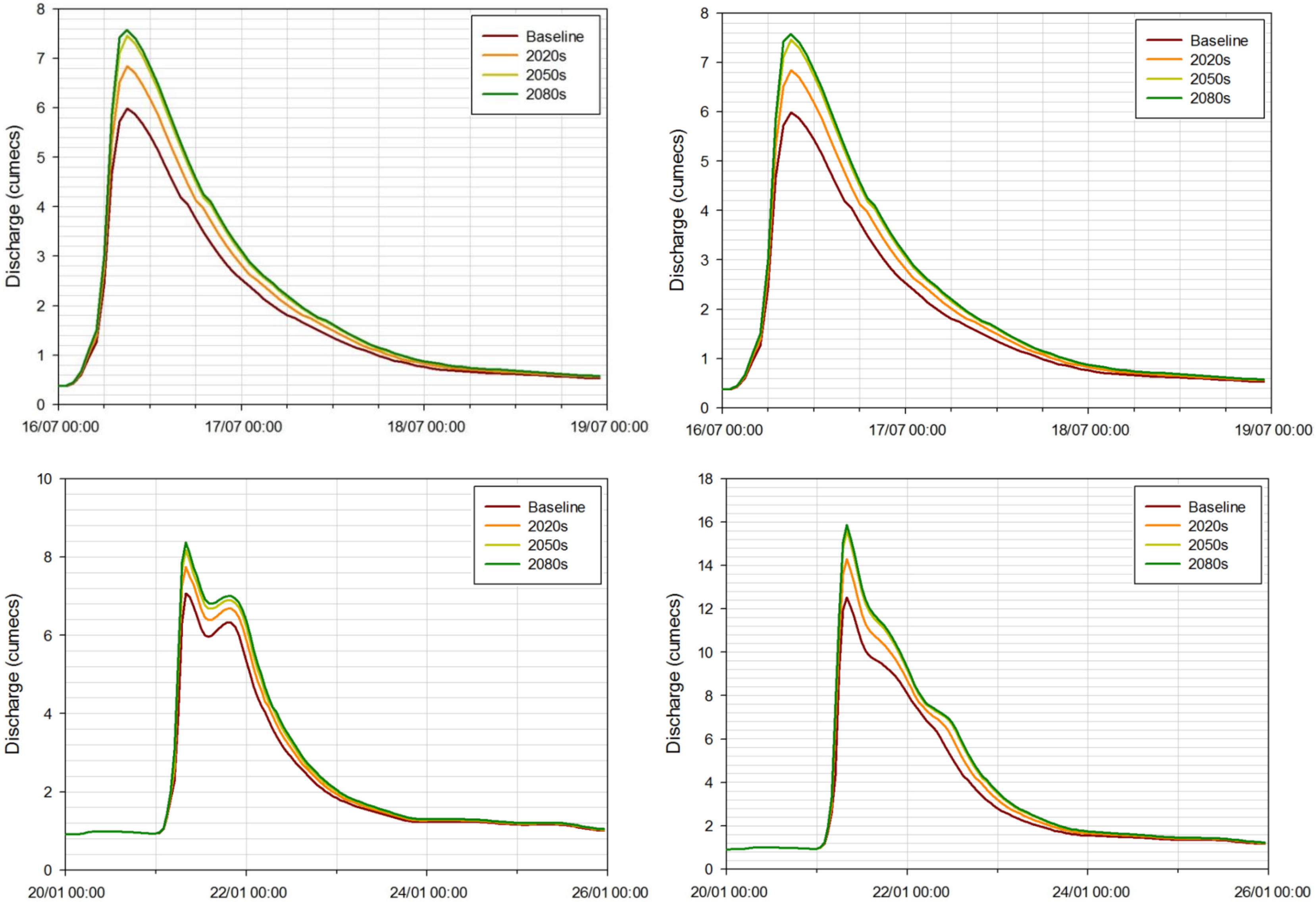

Figure 5.8. Modelled discharge for 7 h duration event for baseline (1961-1990), 2020s, 2050s and 2080s for (a) 10-year return period rainfall event if it occurred in the summer (b) 100-year return period rainfall event if it occurred in the summer (c) 10-year return period rainfall event if it occurred in the winter (d) 100-year return period rainfall event if it occurred in the winter

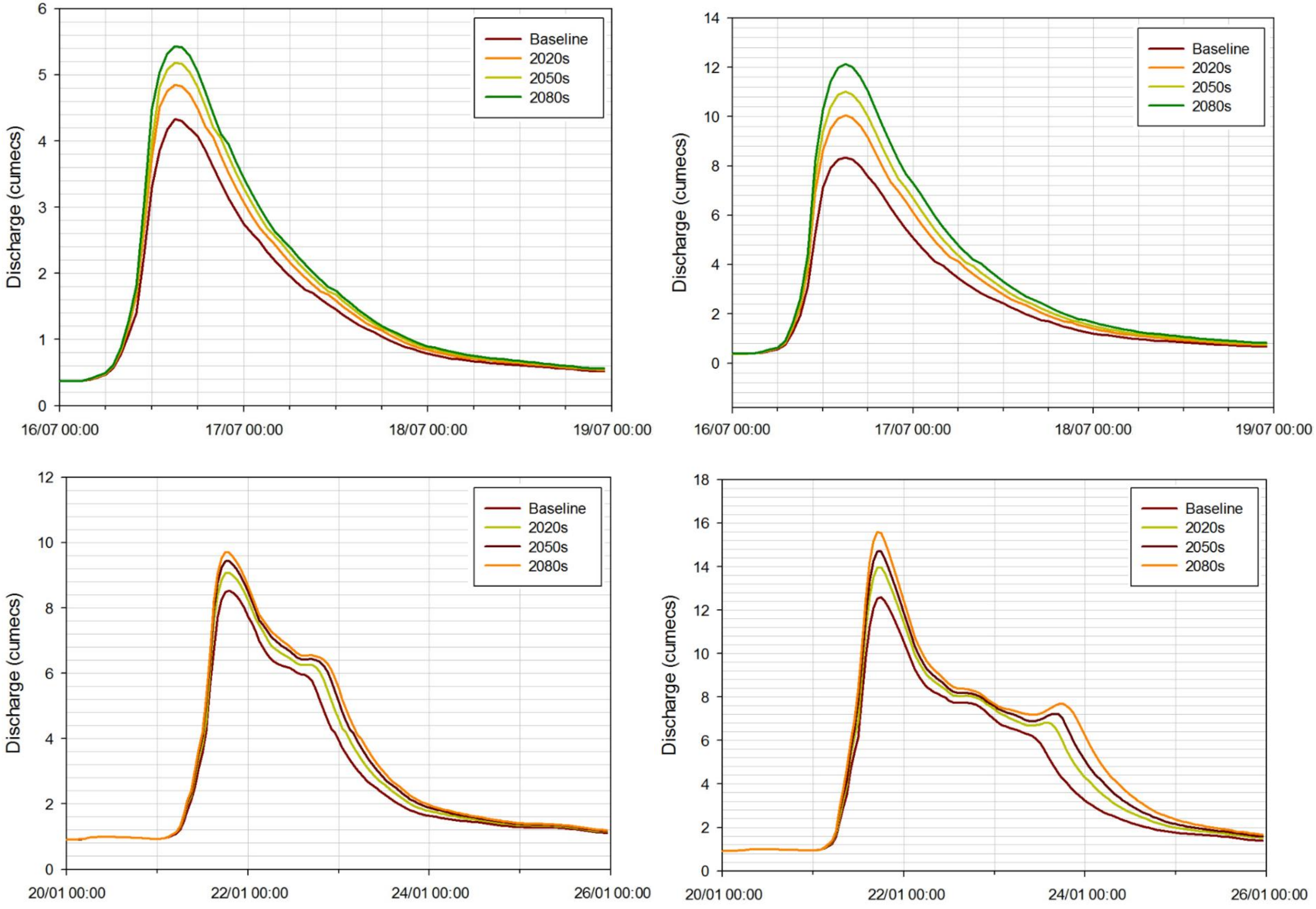

Figure 5.9. Modelled discharge for 15 h duration event for baseline (1961-1990), 2020s, 2050s and 2080s for (a) 10-year return period rainfall event if it occurred in the summer (b) 100-year return period rainfall event if it occurred in the summer (c) 10-year return period rainfall event if it occurred in the winter (d) 100-year return period rainfall event if it occurred in the winter

Table 5.8. The percentage change(%) from the baseline (1961-1190) of the flow peaks for 10 years and 100 years return period events by 2020s, 2050s and 2080s (medium emissions scenario) if they occurred in the summer or in the winter

	Summer 10 year return period		**Summer 100 year return period**		**Winter 10 year return period**		**Winter 100 year return period**	
	7 hour	15 hour	7 hour	15 hour	7 hour	15 hour	7 hour	15 hour
2020s	8.57	15.39	14.14	20.36	9.59	6.55	13.98	10.91
2050s	14.37	25.29	24.47	31.83	15.58	10.70	24.47	16.68
2080s	17.24	32.57	26.42	45.40	18.46	13.89	26.66	23.73

Figures 5.8 and 5.9 present the model simulation results for the current land use for the baseline (1961-1990) and under future climate scenarios (2020s, 2050s and 2080s), for 7 hour events and 15 hour events, respectively.

5.6 Discussion

The modelling results suggest that an increase in the magnitude of extreme weather events is expected for Tarland. The precipitation projections will follow a similar ascending trend established for observed data (Werritty & Sugden, 2013). The changes in precipitation for the 2080s medium emissions scenario from the Weather Generator at Tarland average 19% across different event magnitudes and rainfall event durations, which are within the expected limits of a 1% and 25% increase in average winter precipitation under the medium emissions scenario (Murphy *et al.*, 2009). The baseline for the UKCP09 climate projections as already mentioned is 1961-1990, which means that some of these changes might have already been experienced.

The extreme value analysis highlighted a large degree of uncertainty for the large magnitude rainfall events. The standard deviation increases gradually from a 2-year event to the 1000-year event (as presented in Table 5.3). This can also be seen in the rainfall frequency graph (Figure 5.7) as the large events (1 in 100-year events) for the baseline are within a wide envelope of potential values, and they become even wider for the 2080s. The validation of the 50th percentile rainfall baseline data demonstrated a satisfactory fit with the FEH rainfall levels, giving confidence in the results. Notwithstanding uncertainties in the predictions, which should be fully acknowledged, the results could be used with caution in developing adaptation strategies. Adapting to the 10th percentile changes could leave the system exposed, whilst adapting for 90th percentile changes could have high cost implications. A sensible way forward would be to use the median values as the main indicator of change, but to test the sensitivity of the system for the 10th percentile and 90th percentile change thresholds, in order to be fully informed about wider implications. Specific infrastructure assets (such as nuclear power stations) may need to consider an even higher threshold of up to 99.99th percentile.

It is generally acknowledged that, in the short to medium term, an enhanced flood risk across Scotland is expected with economic, social and environmental costs (Scottish Government, 2011). An increase in precipitation will have a direct impact on discharge. The analysis suggested that peak flows could be by up to 45% larger if an extreme event occurred in the summer, and rising by 27% if the extreme event occurred in the winter (for 1 in 100 year rainfall event).

In Tarland, a shift in the magnitude of extreme weather events is expected to increase the high flows. Flooding problems will put a strain on already vulnerable communities by causing inundation to private properties, businesses and infrastructure, mainly roads and a waste water treatment plant (The Macaulay Institute for Soil Research, 2009). Extended periods of rainfall may also lead to soil erosion, causing agricultural land damage. Moreover this could favour the creation of pathways for nutrient phosphorus transport in the streams, which can exacerbate water quality and eutrophication issues. The aquatic habitat could be negatively impacted as the soil acts as a pollutant smothering fish beds and negatively impacting on aquatic ecosystem function (van Vliet & Zwolsman, 2008). Whilst dredging has been used as a solution to increase the channel capacity and evacuate the excess water, this is no longer seen as a suitable solution for Tarland under the predicted pathways of climate change due to ecologic importance (i.e. Special Area of Conservation designation).

As the frequency of extreme weather events is increasing and high flows become more unpredictable, new solutions are required. The next chapter will assess afforestation and drainage NFM techniques, to contribute to the wider debate of whether NFM options could provide significant flood attenuation potential. The underlying factors which influence their effectiveness, scale and location issues in relation to increased woodland are explored and the impacts of improved drainage assessed.

5.7 Summary

Climate change trends since 1961 demonstrate significant shifts in the precipitation and temperature regime for the east of Scotland. During the 21st Century the annual average temperature is expected to increase by 2 ^{o}C and precipitation could rise by 10% in the winter, whilst decreasing in the summer by an average of 13% (by the 2050s for medium emission scenario). The UKCP09 climate projections also predict an increase in extreme weather events. To understand how this would impact on the Tarland Burn catchment an extreme value analysis was undertaken using hourly data from the Weather Generator, based on the UKCP09 climate projections.

The results demonstrated a significant increase in the rainfall totals for different return periods under alternative climate futures (2020s, 2050s and 2080s medium emission scenario). Changes in the discharge are driven by changes in the rainfall patterns. Modelling results show that under different climate change projections, the discharge is expected to increase for the current land use. The changes will be more marked if extreme events occurred in the summer for 100-year return period events. Under the 2050s medium emission scenario the discharge could increase by up to 25%, whilst for the 2080s medium emission scenario an increase of 27% could be experienced if the extreme event occurred in the winter.

These results strongly suggest that the flood risk in Tarland is expected to increase, with climate change causing adverse impacts on housing and infrastructure, agricultural land and river ecology and habitat. New approaches to achieve greater resilience against an anticipated increased frequency of extreme weather are therefore required.

Chapter 6. Assessment of land use based NFM options: land cover change and drainage

6.1 Introduction

As previously discussed in Chapter 2 the Flood Risk Management (Scotland) Act 2009 is providing the legislative background for sustainable flood risk management and is encouraging the use of NFM options where possible. NFM integrates the principles of EbA, promoting integrated catchment management by using an overarching ecosystem services framework. NFM options utilise natural soil, wetlands and groundwater storage to help attenuate runoff generation and decrease the flooding downstream. Whilst traditional engineering options are well established, NFM options have more recently gained interest and more research is needed to better understand how effective NFM options might be in attenuating the flood risk (SEPA, 2012). This becomes even more important because climate change is expected to increase the flood risk, as demonstrated in Chapter 5.

NFM options were assessed for Tarland in order to test their capacity to alleviate flooding issues in the catchment with a consideration also for their effects on low flows. Evaluation was based upon afforestation options and improved drainage schemes, building therefore on the results from the meta-analysis (Chapter 2). Furthermore land use scenarios have been assessed in order to test the relative influence of land use on flood risk (and low flows). The benefits of using scenarios has been acknowledged in several studies as a way to inform decision making processes related to future change, while incurring relatively low use of resources and financial costs (Peterson *et al*., 2003; Rounsevell *et al*., 2006; Xiang & Clarke, 2003).

Several land use change and drainage density scenarios were set up and the results are presented here along with a discussion of the main findings (see Figure 6.1). Field drainage has been extensively used across Scotland to increase agricultural productivity and access to land by lowering the water table using networks of both surface and subsurface drains (Blanc *et al*., 2012; Newson & Robinson, 1983). The ways in which this extensive drain network is altering the hydrological behaviour has long been investigated. Whilst some studies claim drainage is increasing the flood peaks (Ballard *et al*., 2012; Ballard *et al*., 2010; Nicholson *et al*., 1989; Robinson, 1986) by speeding up the movement of water towards the main channel, others have found that drainage could alleviate flood risk (Iritz *et al*., 1994; Newson & Robinson, 1983), because it increases the soil storage capacity with buffering potential during an extreme rainfall event. A sensitivity analysis of the drainage network was undertaken to understand how improved drainage is altering the catchment's behaviour and to contribute to the wider debate of whether drainage measures contribute to alleviating the flood risk, or have a negative effect by increasing the high flows.

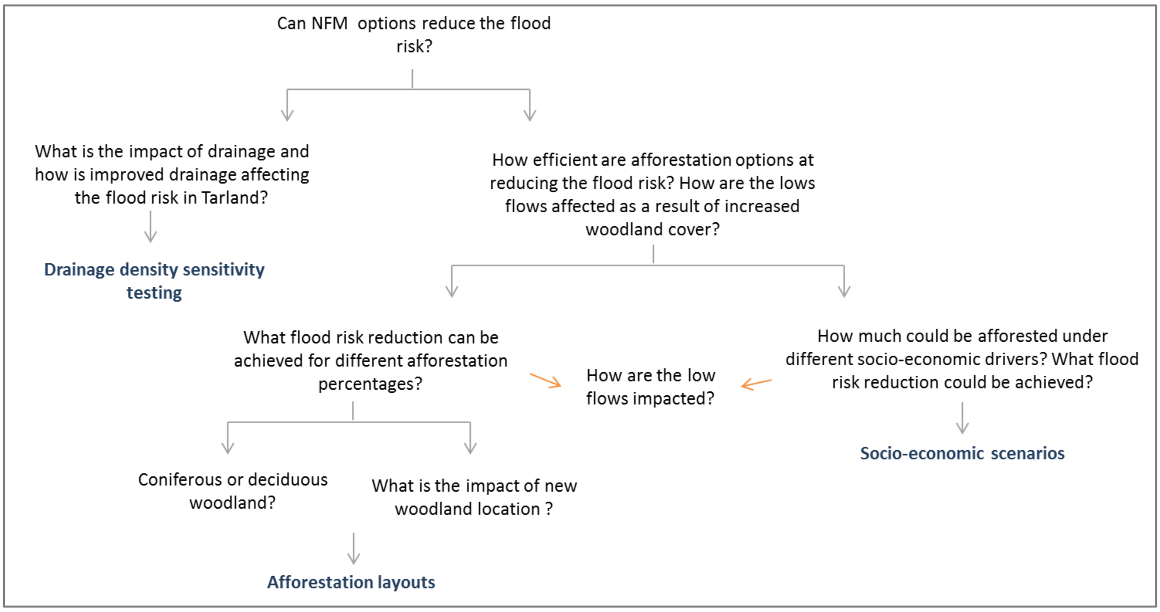

Figure 6.1. The logical sequence used for the analysis in this chapter

Woodland expansion measures are receiving interest from policy makers not only for carbon sequestration and biodiversity but also as an NFM option. There is a need for more evidence to determine whether afforestation measures could be used to attenuate the flood risk in flood prone areas with a consideration for the underlying factors affecting its effectiveness such as spatial and scale issues (i.e. how much land should be afforested and where in the catchment to achieve the highest flood risk reduction) (SEPA, 2012). Moreover, the attractiveness of NFM options lies in their potential to deliver other ecosystem services and understanding what are the benefits, potential disbenefits and trade-offs is key (SEPA, 2012). The placement of new woodland has become increasingly important, as afforestation potential is unevenly distributed across Scotland. Afforestation layouts, each with different percentages of new woodland, were developed to better understand the potential reduction in flood risk during high flows, with a consideration for low flows also.

A large percentage increase of afforestation in catchments such as Tarland, where there is already a competing demand on land to meet different policy objectives, is probably not realistic. The potential for afforestation will be dictated by different socio-economic factors and policy priorities. How these priorities will change in the future is uncertain. Scenarios are tools to consider future possibilities which may go beyond past or current trends. They do not provide predictions or forecasts but rather define the range of possibilities within the context of future uncertainty. Land use scenarios that include complex storylines based on socio-economic drivers were used to investigate the potential of afforestation under different futures, and to establish the implications for flood risk (cf. Brown & Castellazzi; 2014, Rounsevell *et al*., 2006).

6.2 Methodology

Land use scenarios as a means to explore a range of possible futures and assess the effectiveness of different options remain at an early stage of development. Here, scenarios are being used to assess the likely hydrological impact of potential land use configurations and the robustness of different management interventions in reducing flood risks across a range of possible futures rather than to assume only one future pathway and develop responses based upon that. These drivers will impact on the location of new woodland due to competition for land, and then depending on availability of suitable land in each scenario, woodland expansion may be able to expand in the Dee catchment from the current 16% up to 25% consistent with national targets.

The effectiveness of afforestation measures in reducing the flood risk was investigated through sensitivity assessment for different degrees of woodland expansion. The trees are considered as matured in the model through land cover parameters. Maps with varying percentages of afforestation were developed using the LandsFACTS tool and Arc Geographical Information System (ArcGIS) software. LandsFACTS is a land use modelling tool (Castellazzi, 2007; Castellazzi *et al*., 2010) with applications which include creating scenarios of crop rotations for agricultural planning, and changes in land use, making it an appropriate tool for developing maps. The software allows the user to specify spatial and temporal constraints on the land use for each land unit per year. The modelling of the scenarios is based on a stochastic and rule-based approach, to which simulated annealing is added. Different percentages of woodland expansion are tested: 50%, 75% and 100% levels by setting a suite of constraints in LandsFACTS:

(i) new woodland cannot be set for cells already defined as woodland, (ii) new woodland will not be generated for the cells where there are settlements and (iii) new woodland cells will be set at a 100 meters distance from the current ones.

LandsFACTS data were exported to ArcGIS software distributed by the Environmental Systems Research Institute (ESRI), which has wide applications in environmental research. The software was used to derive 100% afforestation scenarios which imply changing the land use of each cell to woodland (except standing water and urban areas). The impact of improved drainage on the runoff response was assessed by comparing the peak flow for different design rainfall events. The rainfall events were inputted into the WaSiM-ETH model and the discharge output analysed against the current conditions in the catchment. Details of the methodology for generating the designed rainfalls are provided in section 6.2.2.1.

The response of afforestation options and land use scenarios on the flow regimes was documented using flow duration curves (FDCs). FDCs show the percentage of time that a specific discharge was equalled or exceeded during a certain period of time (Vogel & Fennessey, 1995). FDCs are ‘the complement of the cumulative distribution function’ of streamflow (Vogel & Fennessey, 1994). The widely accepted Q_5, Q_{50} and Q_{95} represent key attributes of flow regimes in high, median and low flows. FDCs have a long history in the field of hydrology (Vogel & Fennessey, 1994) and are useful tools for water resource development and management analysis (Shaw *et al*., 2011). Whilst it can be argued that FDCs are dependent on the particular recording periods on which their interpretation is based, they are widely used in various areas of hydrology (Vogel & Fennessey, 1994) including to quantify the response of afforestation options on discharge generation (Black *et al*., 1995; Lane *et al*., 2005).

6.2.1 Drainage and afforestation options

6.2.1.1 Drainage

The hydrological behaviour of the Tarland catchment is shaped by both subsurface and surface drainage. Surface drainage can be constructed using shallow trenches or ditches (grips) and it relies on gravity. Subsurface drainage can be either gravity driven or directly pumped and it requires the use of deep open or covered ditches, trenches or by implementing pipe systems (tile drainage) (Blanc *et al*., 2012).

Whilst surface drains can be mapped by comparing pre- and post- drainage survey maps, generally little is known about the location of the subsurface drains in Scotland (Lilly *et al*., 2012). In the 19th century when most subsurface drains were placed in Tarland, the land owners were responsible for keeping records of their installation. Most of this information has apparently been lost, making it extremely difficult to know with precision where in the catchment these subsurface drains are located, how extensive the network is and more importantly how efficient they still are. A recent attempt to survey the sub-surface drains was undertaken by the James Hutton Institute in Tarland, and aimed to assess the functionality of these drains, by checking the mouth of the drains to see which ones are still functioning properly. The survey showed that whilst some drains are still working well, others have been completely blocked but no drainage mapping was attempted.

The drainage network used for the analysis (see Figure 6.2) includes only the surface drains (see section 3.2.1 for more details). Whilst there are limitations in using the drainage information drawn solely from the surface drainage data, there is still great value in conducting this assessment as it contributes to a better understanding of how drainage will impact on the hydrological response of the catchment. The drainage network serves as an exploratory tool to investigate drainage issues and the direction of change (increased or decreased) in relation to flood risk in Tarland.

In the model implementation, the impact of drainage was tested by varying the drainage density parameter. This approach has been used previously to test the effectiveness of drainage at different densities in Germany (Krause & Bronstert, 2007; Wiskow & Ploeg, 2003). The way in which the model represents drainage has been reviewed in Chapter 4, section 4.6.

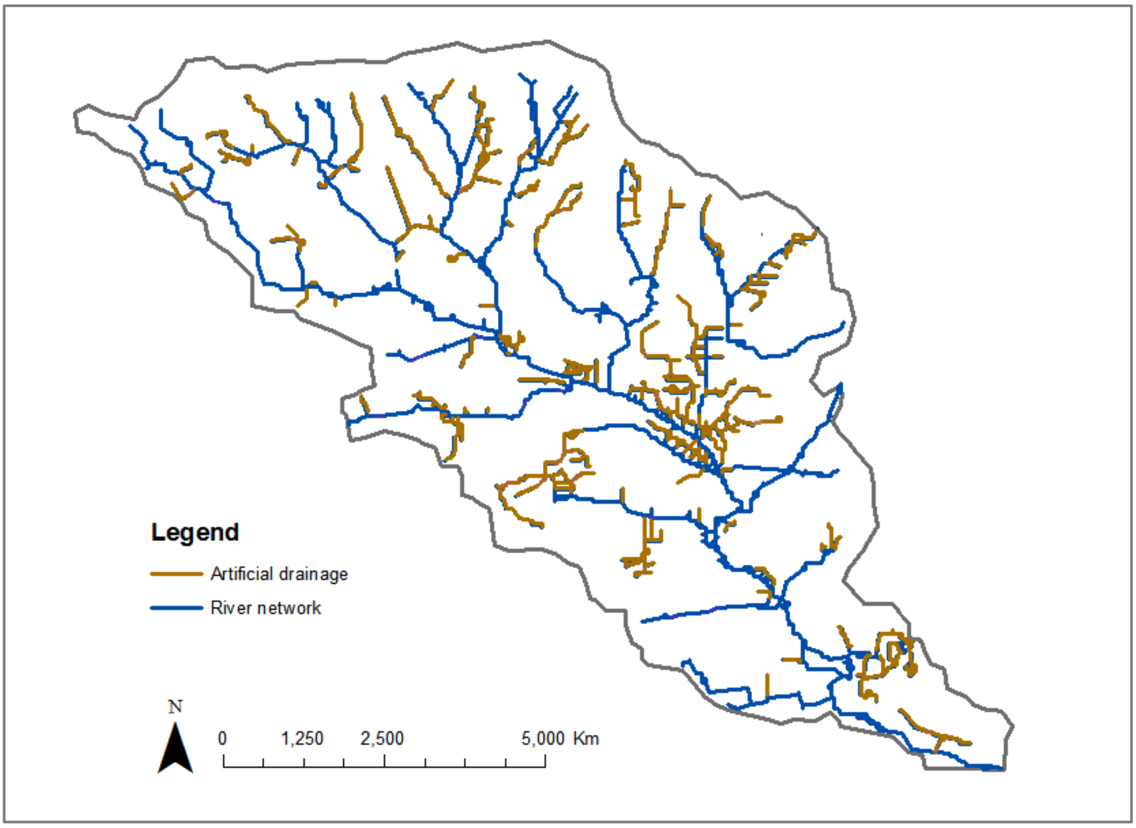

Figure 6.2. Surface drainage network (digitized at James Hutton Institute)

The ‘distance’ parameter for drainage was varied between 5 m to 25 m to represent a spectrum of drainage densities with the density set at 25 m for the current situation. This large distance between the drains would correspond to a situation where many drains are blocked and therefore inefficient, whilst a smaller distance between drains would be associated with a highly effective drainage system in the catchment, where the drains are maintained and unblocked.

6.2.1.2 Afforestation layouts

The afforestation layouts considered different percentages of afforestation relative to the current baseline, distinguishing between coniferous and deciduous woodland. This translates into different scales of woodland coverage, as presented in Table 6.1.

Table 6.1. Percentages of tree increase

Scenario	% woodland	% new woodland	Observations
Baseline	26%	-	26% coniferous and 6% deciduous
No woodland	0%	-	Grassland replaces woodland (both coniferous and deciduous)
National Average	17%	-	9% of woodland (predominantly coniferous) is replaced by grassland
50% afforestation	50%	24%	Trees not planted where there are settlements and standing water
75% afforestation	75%	49%	Trees not planted where there are settlements and standing water
Full afforestation	99%	73%	Trees not planted where there are settlements and standing water

The woodland cover percentage in Tarland (26%) is above the national average in Scotland, at c. 17% (Forestry Commission, 2009). To investigate what the runoff response of the catchment would be if the woodland cover was at the national level, a layout was created where 9% of woodland (mostly coniferous) was replaced with grassland (Figure 6.3 a). A second layout was developed in order to understand how the removal of the current woodland (both coniferous and deciduous woodland being replaced with grassland) would impact on the runoff response in the catchment (Figure 6.3 b).

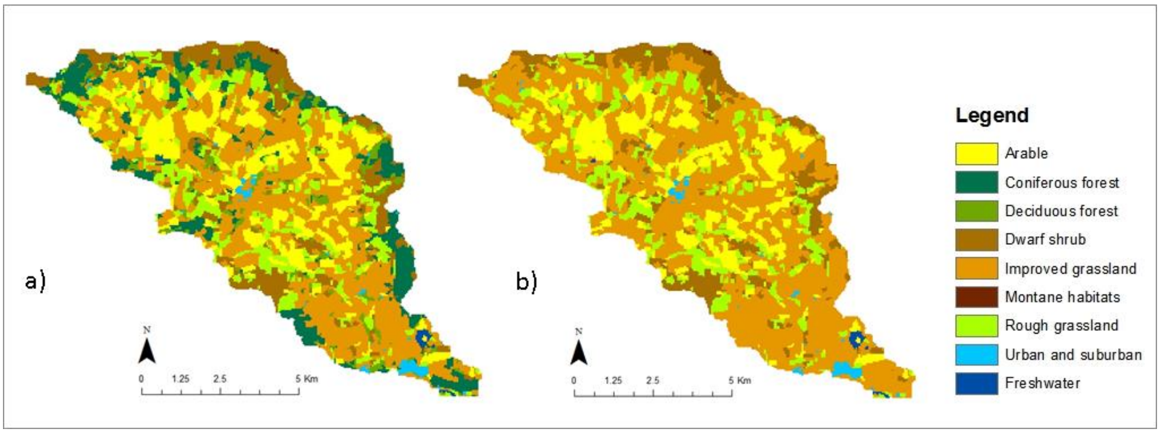

Figure 6.3. Land use scenarios: (a) no woodland in the catchment, replaced by grassland; (b) woodland cover in the catchment is 17% at the National Average level

Afforestation layouts were generated by setting an array of constraints using the LandsFACTS software. To be consistent with the requirement for multiple benefits in afforestation measures, the constraints in the software were set so that new woodland is contiguous with existing sites. Thus the new woodland was defined to be at distances of no more than 100 m from the current established woodland, providing habitat connectivity beneficial for biodiversity (Castellazzi *et al*., 2012). LandsFACTS was run to generate 5 variations of the same afforestation layout, in order to test whether there are any differences in the runoff response and aiming to distinguish changes recorded as a result of increased afforestation percentage from those that may occur due to differences in the locations where the new woodland is planted (Figure 6.4).

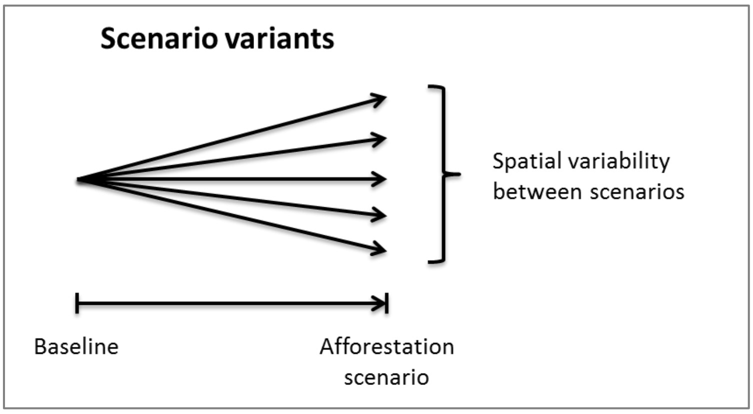

Figure 6.4. Afforestation layouts spatial variations; adapted from Castellazzi *et al.* (2012)

Figure 6.5 and 6.6 present the different spatial realisations of the 50% and 75% afforestation layouts generated using LandsFACTS software.

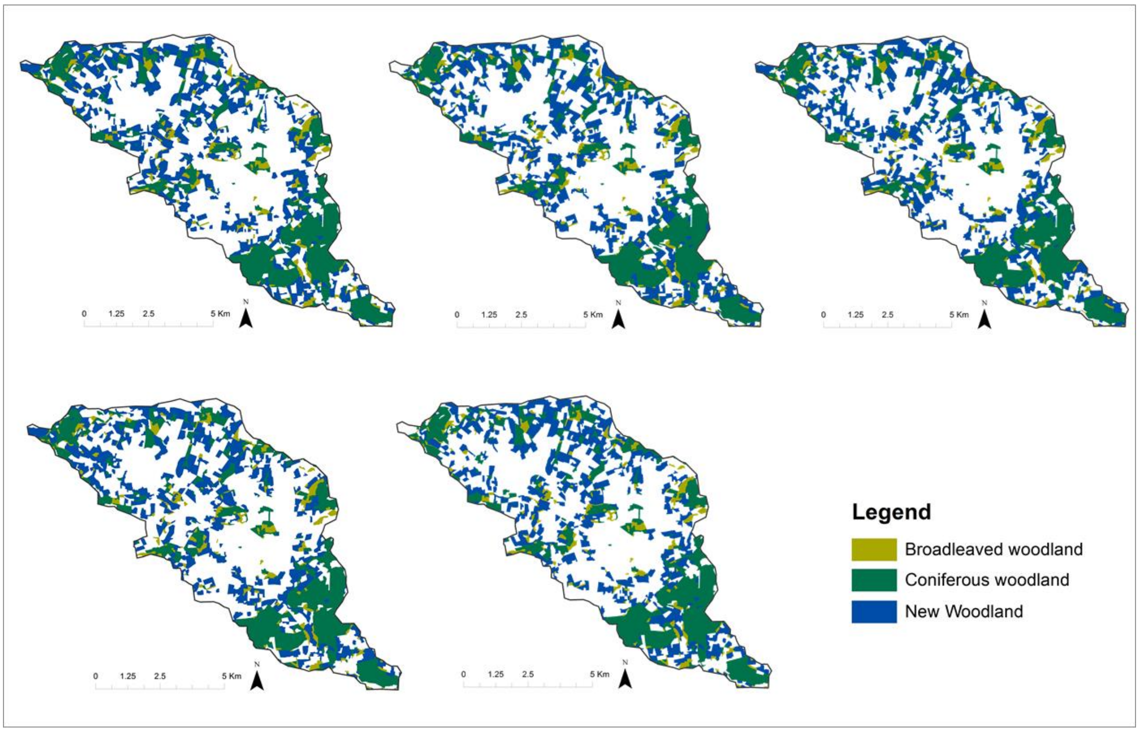

Figure 6.5. Variations of the 50% afforestation map

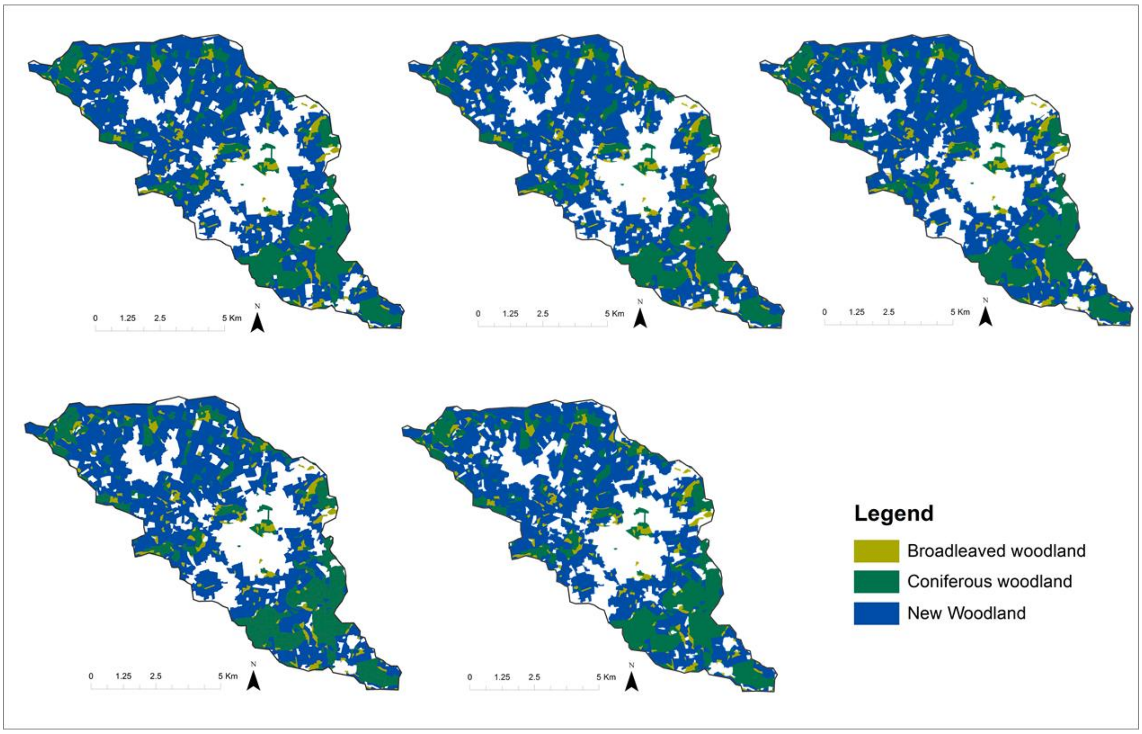

Figure 6.6. Variations of the 75% afforestation map

As seen in Figures 6.5 and 6.6 above, the resulting maps for 50% and 75% afforestation are very similar. This is due to the spatial constraints imposed in LandsFACTS in terms of the land uses that woodland can replace (i.e. not good quality farmland), as these restrict the location of new woodland in the catchment.

6.2.1.3 Socio-economic scenarios

Scenario development has been used by scientists to investigate possible futures, and it was adopted by the IPCC for the Special Report on Emission Scenarios (SRES: Nakicenovic *et al.*, 2000) which formed the basis for future IPCC climate change scenarios prior to their recent 5th assessment report. The IPCC SRES framework provides a global structure to contextualize development of regional socio-economic scenarios that are 'coherent, internally consistent and plausible description of a possible future state'(Brown & Castellazzi, 2014). The framework is based on a two axis approach to describe a range of future demographic, technological and behavioural changes (Figure 6.7). The four SRES storylines represent different futures across two dimensions (i) economic versus environmental values, (ii) global versus regional governance (Brown, 2011). Based on the IPCC SRES scenarios four general storylines have been adopted for the present study with additional details borrowed from the UKCIP socio-economic scenarios (Berkhout *et al.*, 2002) to produce scenarios for the

NE of Scotland. For local details, stakeholder events have previously provided feed-back in the development of Tarland specific storylines with specific emphasis on possible land use change (Brown & Castellazzi, 2014).

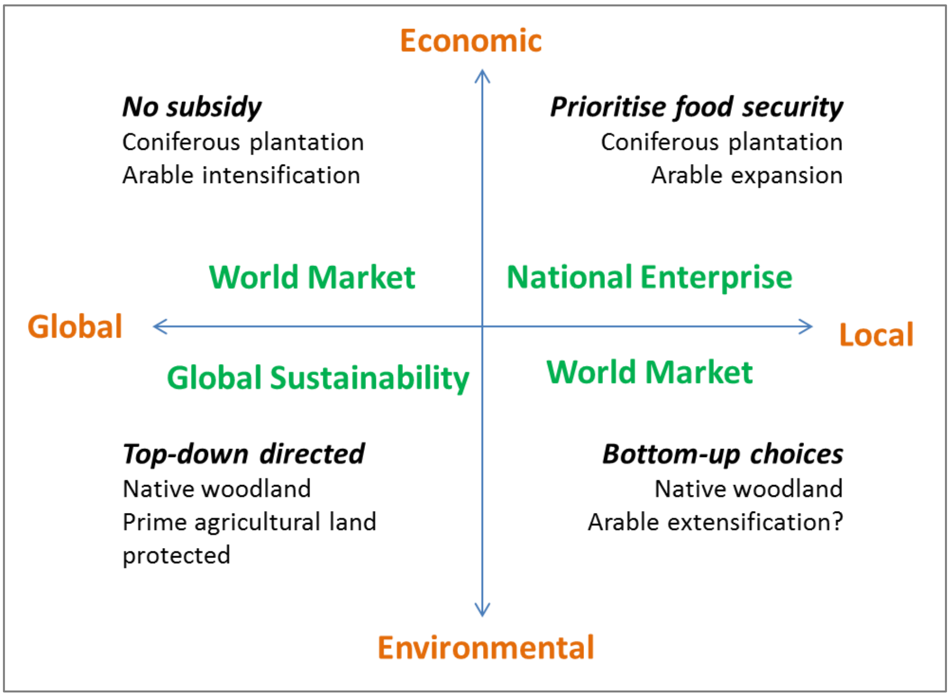

Figure 6.7. Land use storylines for the Tarland catchment; adapted from Brown & Castellazzi (2014)

The scenarios specific to Tarland were developed as part of the REFRESH project, an International EU project with partners from several European countries. The main aim of the project was to investigate the relative influence of climate and land use change on water quality together with adaptation options to meet policy objectives in the WFD, including collaboration and engagement with local land farmers.

The storylines are driven by a combination of policy priorities and constraints upon the use of natural resources with specific emphasis on land use (Figure 6.8). Two land use changes are considered for these scenarios: woodland expansion and arable land variations (see Figure 6.9). All storylines account for the biophysical restrictions to land use changes in 2050, explicitly integrating the impact of climate change on water resources through land use change. The UKCP09 climate projections (Murphy *et al*., 2009) indicate drier summers under most scenarios for this region, which will improve the land capability of the Tarland catchment and could be used to increase food production (Brown, 2011, Brown *et al*., 2008).

World Markets: This scenario features a rapid economic growth and technological advancement based on globalisation. The population growth is relatively low, wealth increases and materialist consumerist values predominate. The key responsibilities and rights for flood management would lie with the owner (managed through weak agencies) with a prevalence for hard engineering options and low regard for environmental impacts. Agriculture is market driven and irrigation would only be used for high value crops.

National Enterprise: This scenario describes a rapid population growth though with lower economic growth due to inconsistent development across the world, with an emphasis on co-operation only among similar cultures. In Europe this translates into strong national policies with common policy development. Similar to the World Markets scenario, responsibility lies with the land owner and hard engineered defences are preferred to meet immediate needs. Food security is very important and large scale irrigation is an option for all priority crops (including energy) and supported by food security subsidies.

Global Sustainability: This scenario has a focus on environmentally sustainable approaches to achieving worldwide solutions that balance social, economic and environmental targets at a global scale. National and supranational agencies and standards ensure a consistent approach applied everywhere. Land use and water resources are managed through a multi-benefit integrated catchment approach with a preference for NFM measures. At a catchment scale both upstream and downstream issues are considered and irrigation would only be implemented where water resources are plentiful, to protect water quantity and quality.

Local Stewardship: In this scenario the criteria for sustainable social, environmental and economic development are being tailored to meet the demands of local agencies with a significant input from the local community through public participation. Flood and water resource management are integrated with land use management but the downstream implications are not being considered and managing large basins covered by different interest groups may be difficult. To protect water bodies and support food production, local agreement between stakeholders might be achieved.

Figure 6.8. Land use scenarios storyline (Brown & Castellazzi, 2014)

The rule-based constraints given in LandsFACTS to generate the quantitative spatially-explicit scenarios, are in accordance with each story line, in the sense that they restrict the extent of new woodland and where it can be located in the catchment. Although multiple realisations of each scenario were generated, the constraints actually meant that there is very little difference between different variations of the scenarios (Brown & Castellazzi, 2014), so only one representative realization for each scenario was considered necessary for the assessment of hydrological impact. The scenarios achieve different levels and types of afforestation, as presented in Table 6.2.

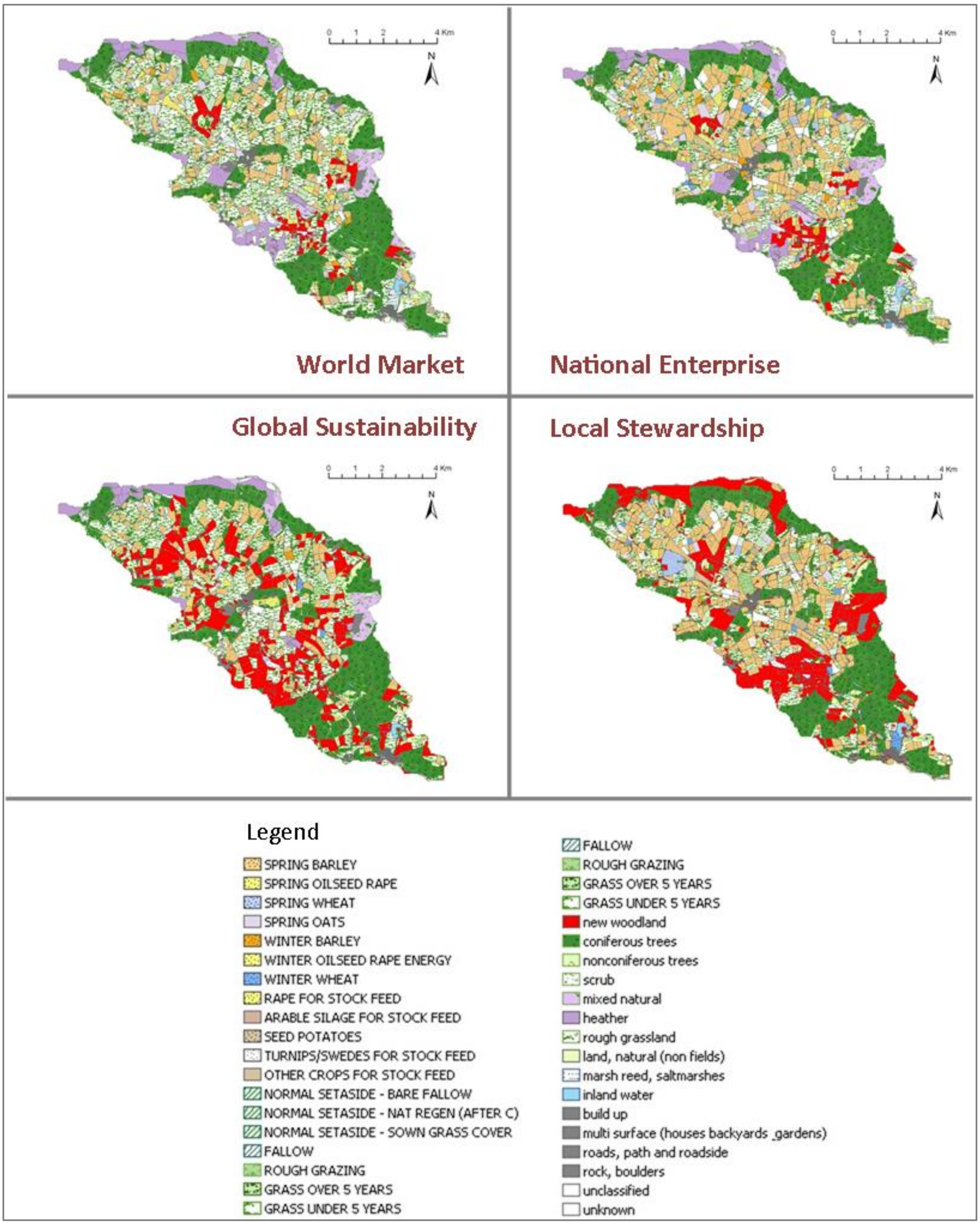

Figure 6.9. Socio-economic scenarios for 2050s (Brown & Castellazzi, 2014)

Table 6.2. Afforestation percentage in the socio-economic scenarios

Scenarios	Percentage woodland (%)	Type of woodland added
Baseline	26	-
World Markets	30	Coniferous
National Enterprise	30	Coniferous
Global Sustainability	47	Deciduous
Local Stewardship	47	Deciduous

To understand how the land use scenarios will impact on the low and high flows, a comparison between the scenarios was undertaken using the baseline data (1961-1990).

6.2.2. Meteorological data used for the drainage and afforestation options assessment

6.2.2.1 Meteorological data for drainage sensitivity testing

The hydrological response inferred by simulations using hydrological parameters in the WaSiM-ETH model was tested for a range of precipitation event durations and for different event magnitudes. The meteorological data for drainage sensitivity followed the methodology described in detail in the previous chapter (Chapter 5). The 7 hour and 15 hour precipitation events were calculated from the Weather Generator baseline data and the extreme value analysis was undertaken to calculate the return period for precipitation events.

Table 6.3. Extreme value analysis results for 100 baseline data outputs from the Weather Generator

Return period	Mean 7 hour	Mean 15 hour
2 year	24.93	30.86
5 year	32.83	40.86
10 year	**38.58**	**48.19**
20 year	44.58	55.89
50 year	53.26	67.03
100 year	**60.57**	**76.43**
200 year	68.69	86.88
500 year	80.97	102.68
1000 year	91.69	116.46

The calculated 10 years and 100 years return periods (see Table 6.3) were further used for the analysis and redistributed into hourly data using the FEH method included in the ISIS software (Institute Hydrology, 1999) (Figures 6.10, 6.11).

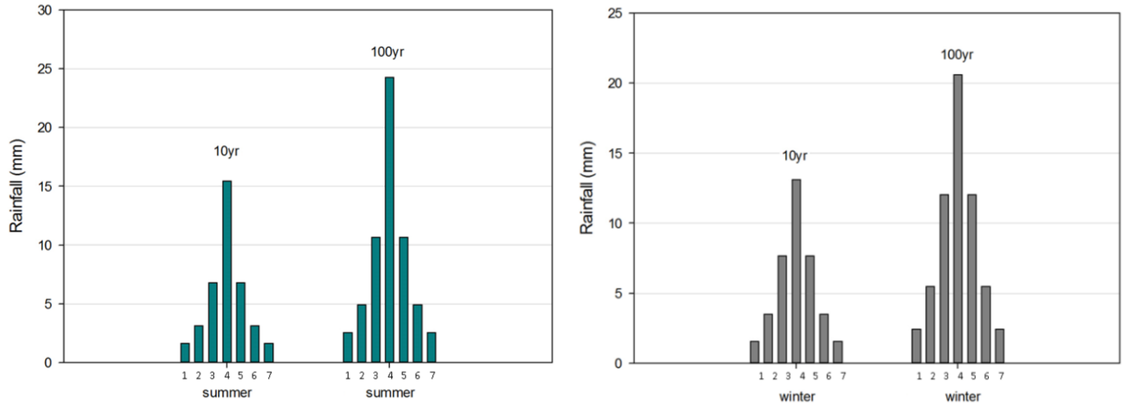

Figure 6.10. Hourly rainfall profiles generated using FEH distribution method for 7 hour event duration for (a) summer and (b) winter

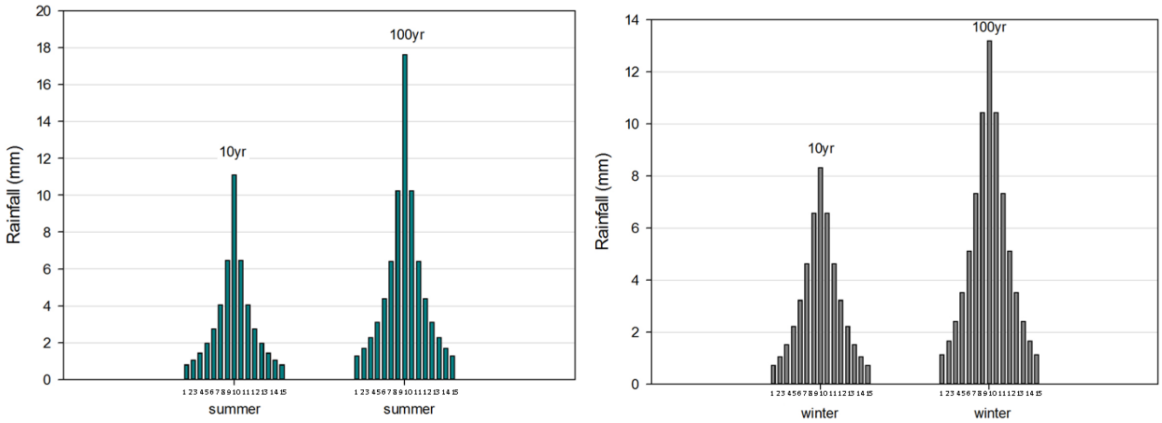

Figure 6.11. Hourly rainfall profiles generated using FEH distribution method for 15 hour event duration for (a) summer and (b) winter

The assessment of drainage options was considered for summer and winter events and the WaSiM-ETH hydrological model was trained with winter and summer meteorological data for the model simulations.

6.2.2.2 Meteorological data for afforestation layouts and scenario testing

The meteorological data used for assessing the afforestation scenarios are synthetic baseline data drawing on the 1961-1990 meteorological data downloaded from the Weather Generator. Synthetic data have been used because long term records for all the meteorological parameters (precipitation, temperature, sunshine duration, wind, air humidity) required in WaSiM-ETH are not available for the Tarland catchment. The annual rainfall and the average temperature of the synthetic time series used for the afforestation scenarios are presented in Figures 6.12 and 6.13.

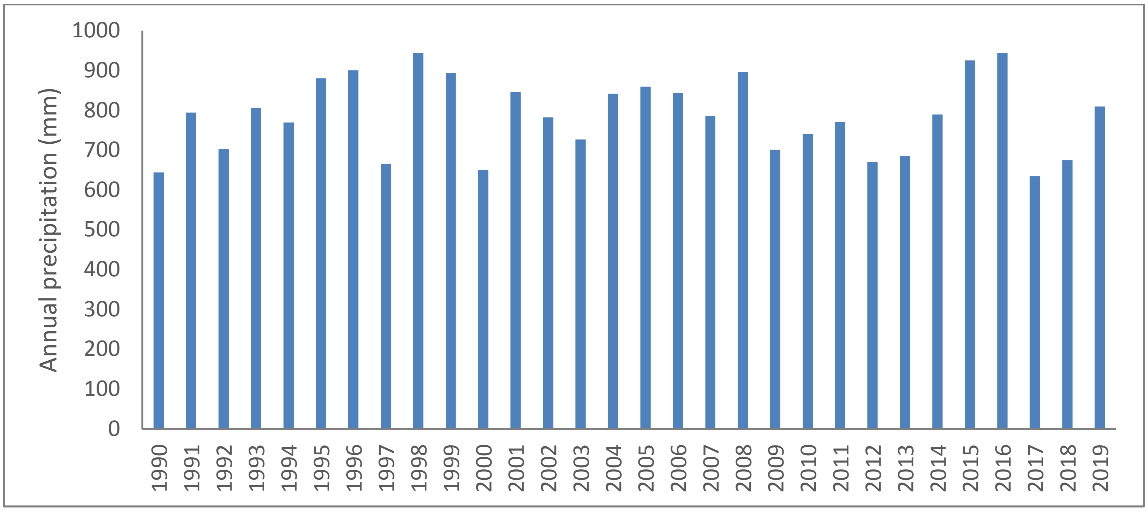

Figure 6.12. Annual rainfall for baseline data from the Weather Generator used to assess the afforestation scenarios

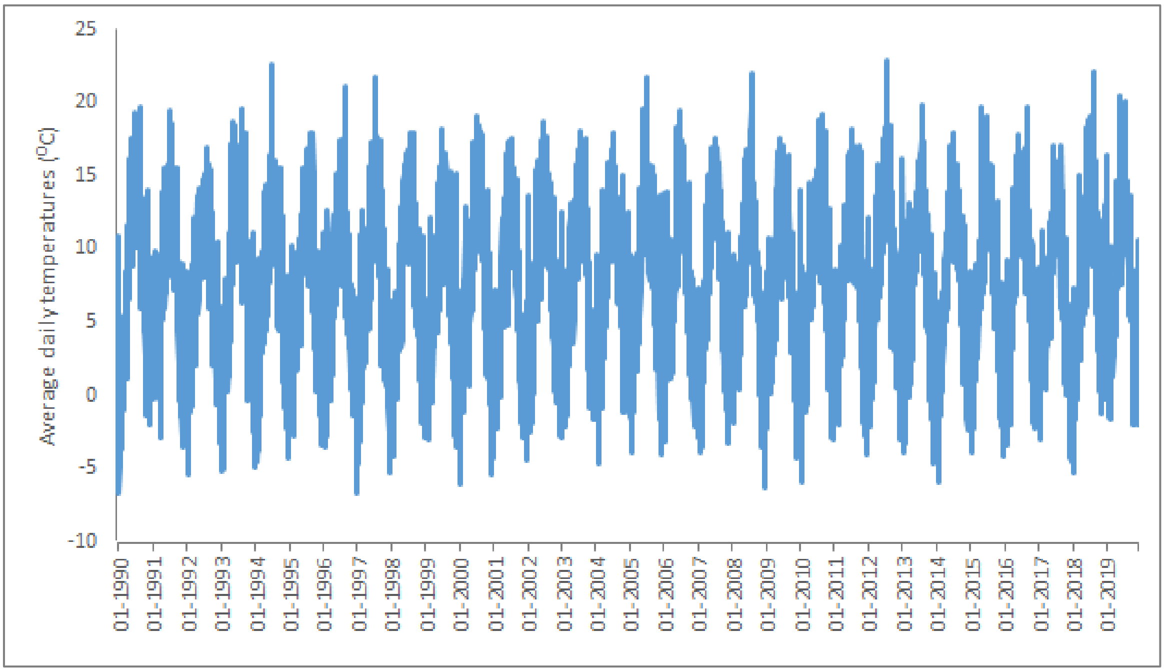

Figure 6.13. Average daily temperature for baseline data from the Weather Generator used to assess the afforestation scenarios

The rainfall data were validated against the FEH (Institute Hydrology, 1999) depth-duration-frequency rainfall statistics. To this end the return period was calculated following the methodology described in Chapter 5 (see Table 6.4). The high level of agreement between the observed (FEH) rainfall totals and the selected Weather Generator baseline data provides confidence that the synthetic rainfall used for the analysis is adequately representing the rainfall extremes and is appropriate for the analysis.

Table 6.4. Comparison between the return period rainfall totals for the observed (FEH) and synthetic baseline data

Event duration	Return period	Observed (FEH)	Synthetic baseline M1
7 hour event	10	**35.10**	**36.86**
	100	**55.49**	**57.15**
15 hour event	10	**49.53**	**47.84**
	100	**76.23**	**79.79**

6.3 Results

6.3.1 Drainage sensitivity testing

The results show that modified drainage network through increased drainage density has the potential to lower the discharge peaks in the summer (Figure 6.14). For extreme rainfall events of 10 years return period, improved drainage (i.e. 5 dis) could reduce the peaks by up to 9.5%. A comparable decrease in peak flow was also noted for large events (i.e. up to 9% for a 1 in 100 year return period rainfall event). The denser drainage system increased soil storage capacity and contributed to a reduction in surface runoff, and consequently flood peaks were reduced due to the lower water table prior to the heavy rainfall event.

The benefits of improved drainage systems were less prominent in the winter (Figure 6.15) than in the summer, because wet antecedent conditions will generate larger flood peaks for the same extreme event magnitude (different rain profile). In the winter the water table is high because the drainage network cannot remove the surplus water, and there is little storage available in the catchment (i.e. it is at or close to field capacity). As a consequence improved drainage will offer marginal reductions of only 2% to 5% of the discharge peaks for 10 year and 100 year return period events. In addition, improved efficacy of the drainage system will lead to an increase in the baseflow in the winter, as shown by model results, with field measurements having demonstrated similar findings (Robinson, 1985).

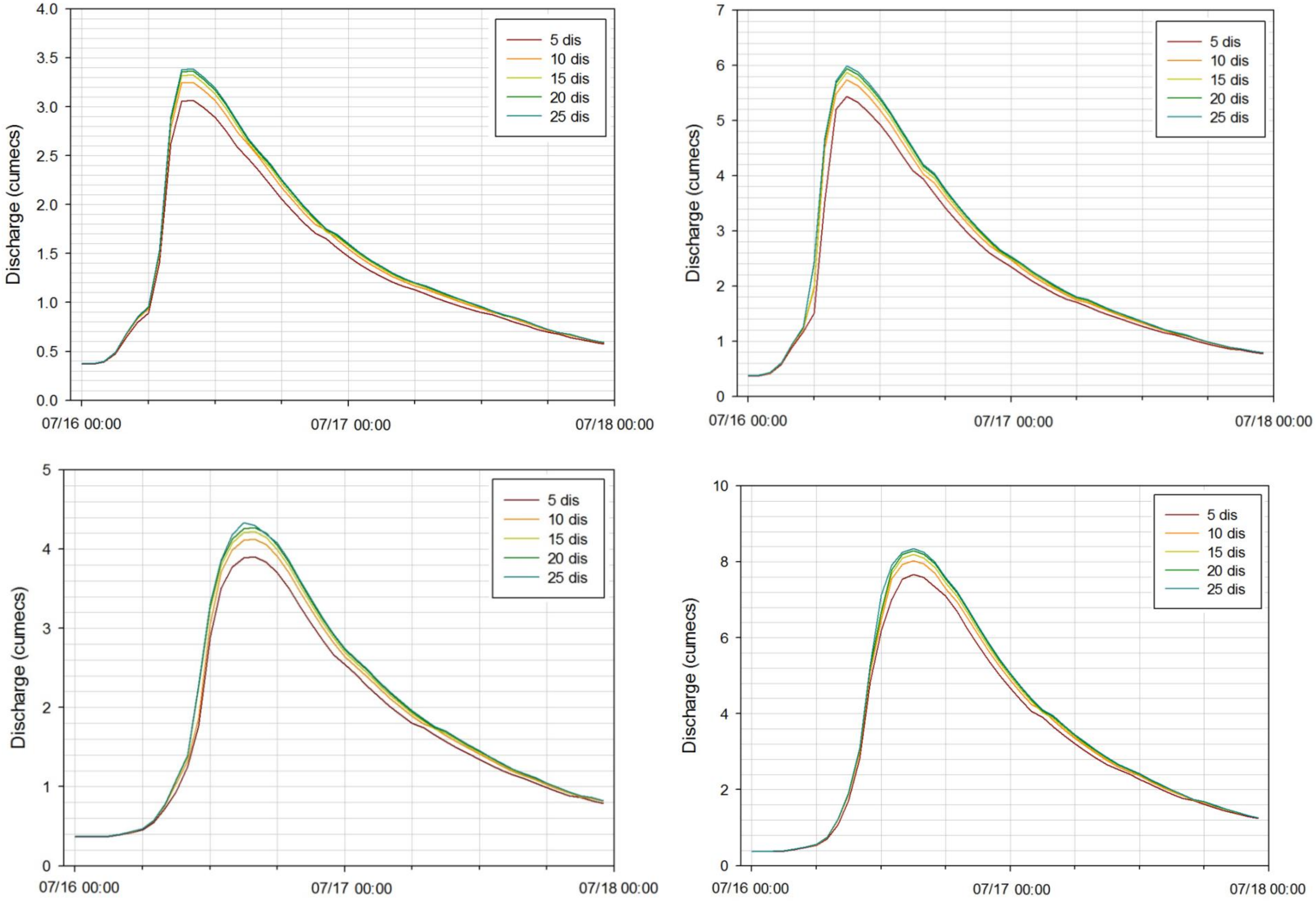

Figure 6.14. Varying drain spacing modelling results for summer for (a) 7 hour 10 year return period, (b) 7 hour events for 100 year return period, (c) for 15 hour events for 10 year return period and (d) for 15 hour events for 100 year return period

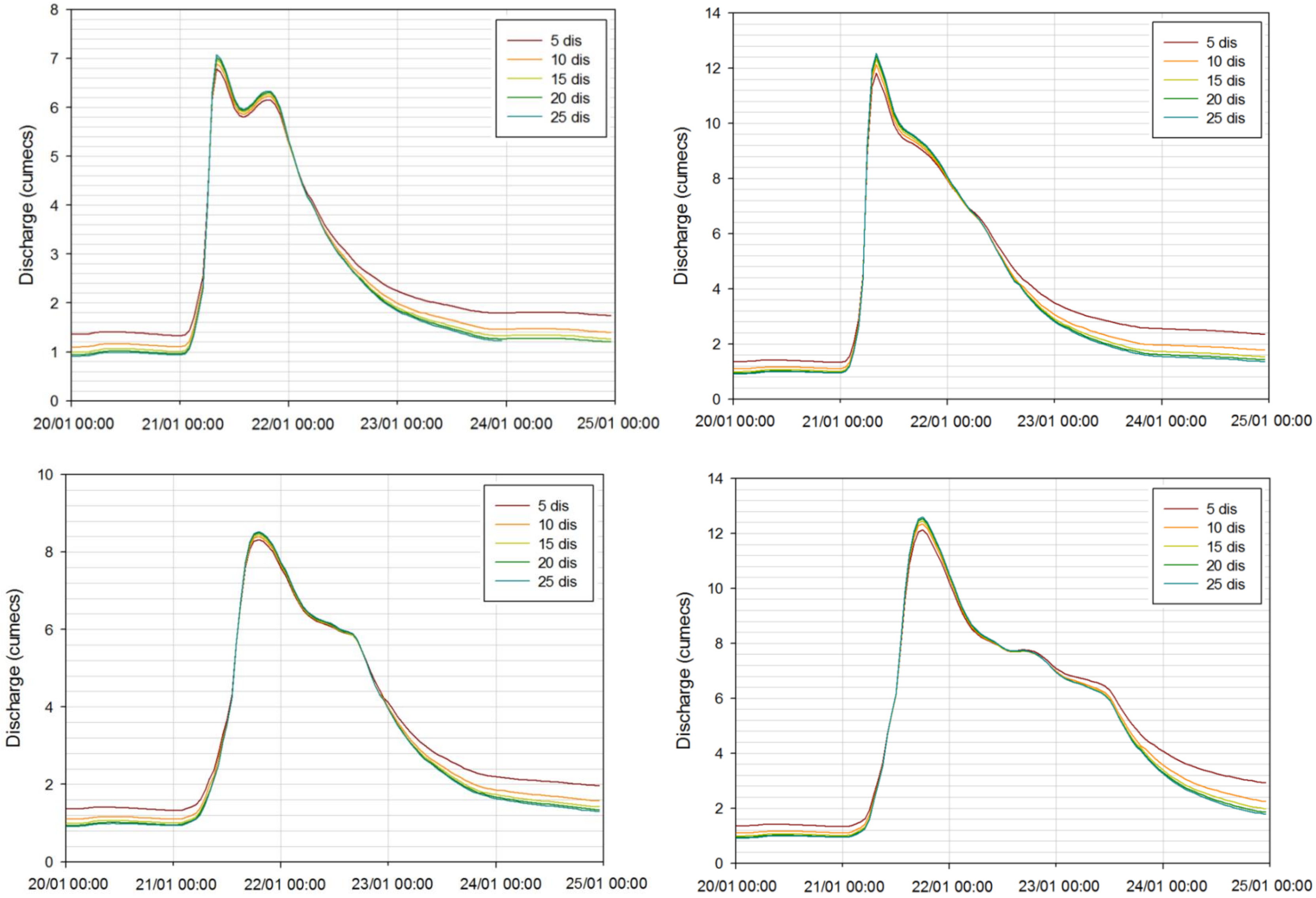

Figure 6.15. Varying drain spacing modelling results for winter for (a) 7 hour 10 year return period, (b) 7 hour events for 100 year return period, (c) for 15 hour events for 10 year return period and (d) for 15 hour events for 100 year return period

6.3.2 Assessment of afforestation options

The modelling exercise using different woodland covers showed significant variations in key hydrological indices - Q_5, Q_{50} and Q_{95} (see Figure 6.16). Whilst increasing the woodland cover was noted to decrease the high flows, the National Average woodland cover scenario and No woodland scenario showed increases in the Q_5 and higher levels for Q_{95}. The impact of afforestation both on low flows and high flows was found to be more pronounced when new woodland consists of coniferous rather than deciduous trees.

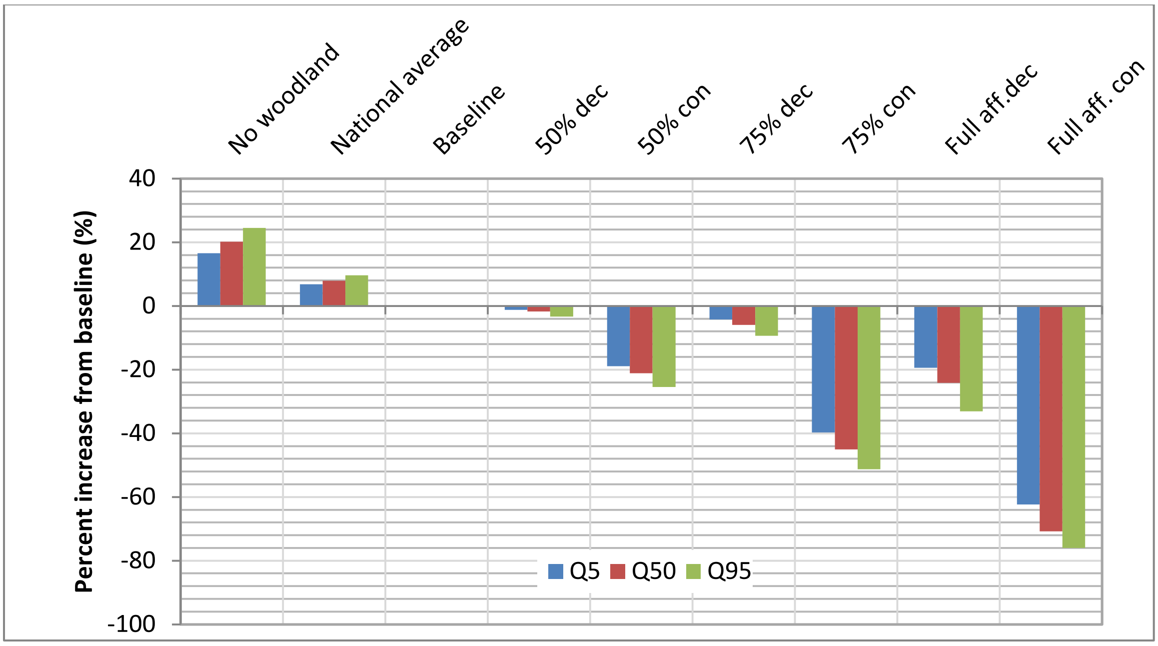

Figure 6.16. Percentage increase of Q_5, Q_{50} and Q_{95} from baseline of different afforestation scenarios

The FDCs for the baseline and the afforestation layouts is presented in Figure 6.17. The curve is very steep in the upper part with high flows for short periods, which are predominantly rain caused floods, and with fewer snow events, largely fed by direct runoff. The distribution of the high flows is governed mostly by climate, the physiography and the plant cover of the basin. The curve is flat in the lower part, indicating that moderate flows are sustained throughout the year due to natural or artificial regulation and groundwater capacity which sustains the baseflow to the stream (Shaw *et al.*, 2011). The flow curve shows significant lower levels throughout, for increased degrees of afforestation. The impact of afforestation layouts on the runoff response, when considering high flows and low flows, is presented below.

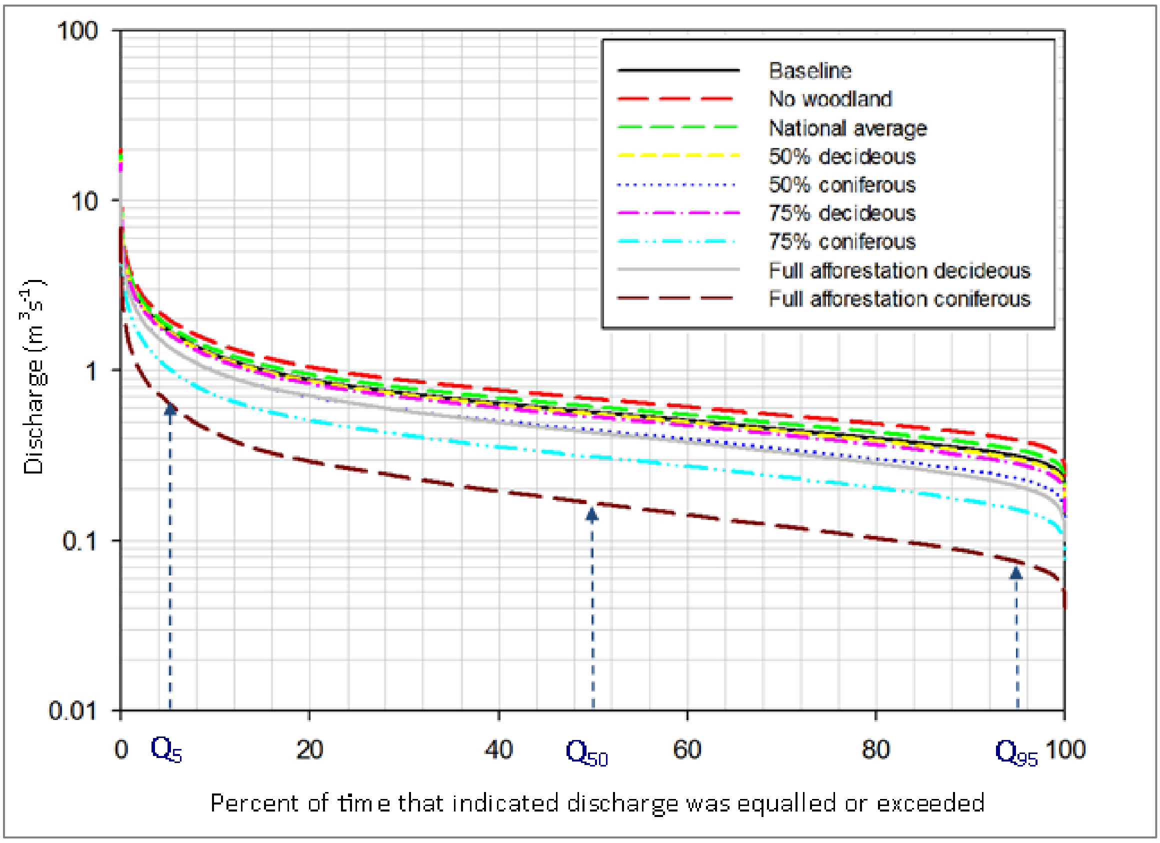

Figure 6.17. FDCs for the current land use and the afforestation layouts

6.4.2.1High flows

Model simulation results suggest that increasing the woodland cover will decrease the high flows (Q_5), dependent on the percentage of afforestation and the type of tree being used (Table 6.5, Figure 6.18).

Table 6.5. The impacts of the afforestation layouts on the Q_5 in Tarland

Afforestation layout	Q_5 (m^3s^{-1})	Percentage increase (%)
No woodland	1.999	16.57
National average	1.832	6.84
Baseline	1.715	0
50% deciduous	1.694	-1.22
50% coniferous	1.391	-18.87
75% deciduous	1.643	-4.21
75% coniferous	1.033	-39.74
Full afforestation deciduous	1.382	-19.43
Full afforestation coniferous	0.646	-62.35

The largest runoff reduction can be achieved when the whole catchment is afforested with coniferous trees, with a reduction of the Q_5 of 62%. However if the catchment is fully afforested with deciduous woodland, then the Q_5 will record a decrease of only

19%. If 75% of the catchment is covered in coniferous woodland, i.e. an increase of 49% afforestation from the baseline, then a reduction of c. 40% of the Q_5 can be achieved. The same level of afforestation with deciduous trees will register a reduction of only 4.2% in Q_5 compared to the baseline. Intriguingly a woodland expansion of 24% from the baseline (50% representation coverage configuration) with coniferous trees would generate similar changes in the Q_5 as a 74% increase in woodland (full afforestation) using deciduous trees. This clearly suggests that by concentrating efforts in the planting of coniferous woodland, significantly reduced levels can be achieved for lower values of afforestation. The National average and No woodland afforestation scenario showed that the removal of existing woodland would increase the high flows (~6%, respectively ~16%) suggesting that the forest in the catchment is already providing a flood protection function in Tarland

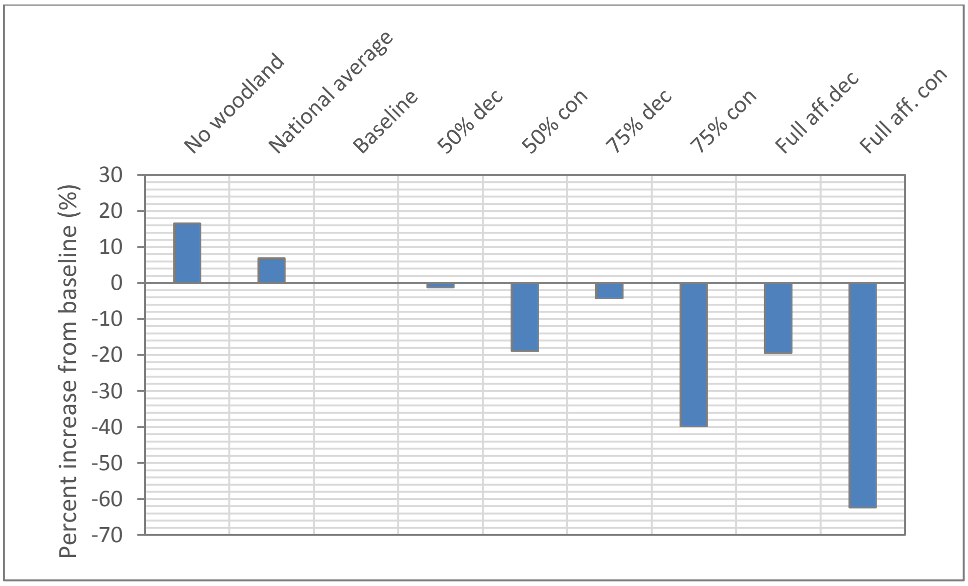

Figure 6.18. Percent change of Q_5 from baseline for the afforestation scenarios

The percentage decrease in discharge for every 1% increase in new woodland in the catchment was calculated and presented in Figure 6.19. For every 1% increase of coniferous woodland an average 0.8% decrease in the discharge corresponding to a Q_5 level will be achieved, whilst for deciduous woodland this decrease is lower, with an average of only 0.15% for every 1% of new woodland coverage added.

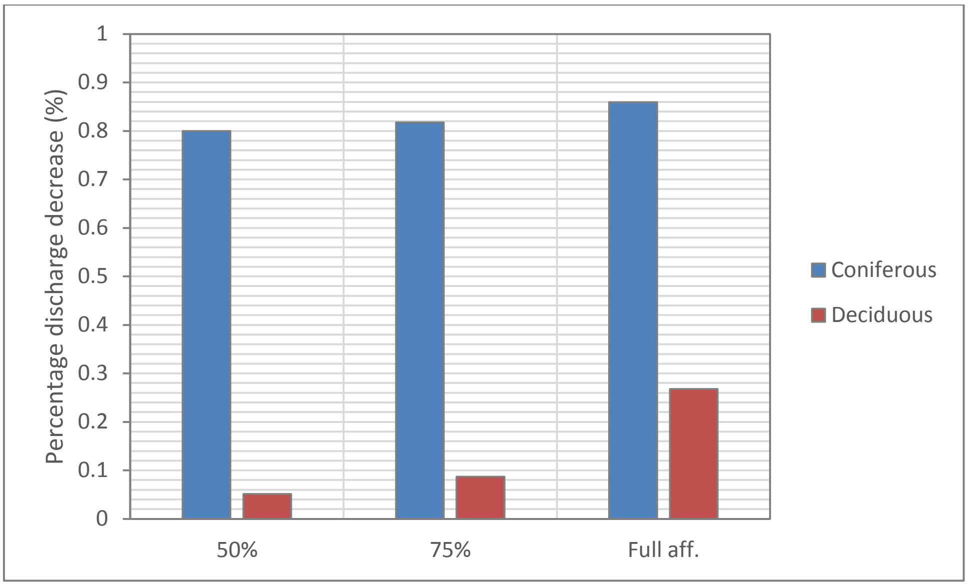

Figure 6.19. Percentage decrease of discharge for a Q_5 level

Variation in the percentage decrease in discharge for every 1% shift in woodland cover can be seen for coniferous and deciduous woodland at different stages of afforestation. This variation is a result of contrasts between the land use types that are being replaced. Converting arable land to woodland will generate the highest impact in the runoff response, followed by grassland and dwarf shrub. This is a result of above ground change and varying land use coefficients, which lead to different capacities (Calder, 1990, 1998; Hall *et al.*, 1996) in removing water from the catchment through evaporation and transpiration. With lower levels of afforestation (50%) there are more options for where new woodland can be placed, though subject to the set of constraints imposed in the LandsFACTS software. As the percentage of afforestation increases (75%) there are fewer possible configurations for the inclusion of new woodland; as a consequence more arable land cover must be converted to woodland, which generates larger decreases in runoff.

The variation between the 50% and 75% scenarios has been tested and the results are shown in Figure 6.20. The results suggest that there are very small differences in Q_5 for different configurations of afforestation. However the apparent insensitivity of afforestation to location is not necessarily a real measure of the effect of location in reducing the flood risk. As already discussed in section 6.2.2 and seen in Figure 6.5 and 6.6, the scenario variants are themselves very similar, generating little variation in the results.

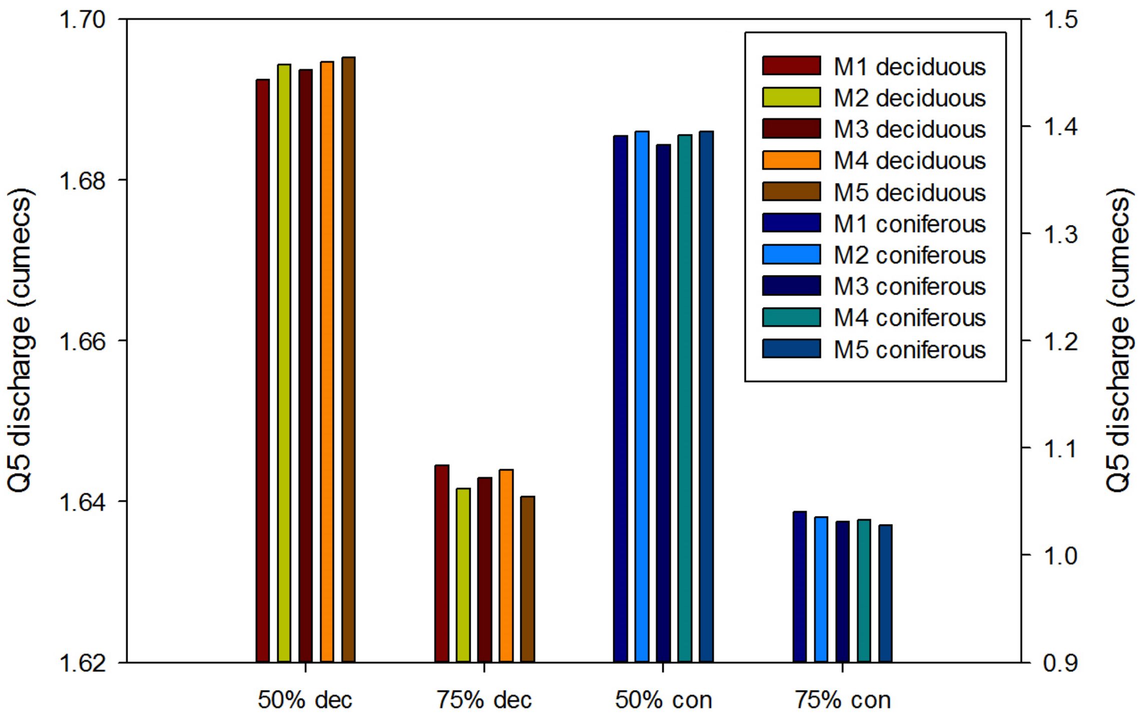

Figure 6.20. The difference between different realizations of the 50% and 75% afforestation levels with coniferous and deciduous woodland for Q_5

The changes in river discharge discussed so far are based on the Q_5 levels; however, these are in-channel events that do not result in damaging overbank flood events. It is expected that afforestation options will be less effective at reducing the over-channel events than the in-channel events. For flow levels corresponding to a 1 in 2 year flood i.e. 7.4 m^3s^{-1}, the discharge reduction is less, compared with Q_5 levels. Full afforestation with coniferous woodland will decrease the 1 in 2 year flood event level by 57% (compared with 62% for Q_5) which suggests that the efficacy of afforestation options at reducing the runoff decreases for higher over-channel flood events.

Model results indicate large differences between coniferous and deciduous trees, for the same percentages of afforestation. The main factor contributing to this difference is the evapotranspiration rate for the coniferous woodland compared to deciduous woodland. The two components of evapotranspiration, interception and evaporation, both vary importantly for the two types of woodland. Traditionally, transpiration is considered the most important component of forest evapotranspiration, however interception and consequent evaporation from the canopy can also increase substantially, particularly for coniferous woodland (Cannell, 1999). Several studies show differences in interception values between coniferous and deciduous forest stands, by as much as 35%. In this way, coniferous woodland can intercept and evaporate 25 - 45% of the total annual precipitation, whilst broadleaved woodland can intercept and evaporate 10 - 25% of the total annual rainfall (see Figure 6.21) (Calder *et al*., 2003). Forest transpiration rates are influenced by changes in rooting network, leaf area index, stomatal response, albedo and aerodynamic turbulence (Hoffman & Jackson, 2000; Jackson *et al*., 2001). Whilst significant differences have been noted for interception between coniferous and deciduous trees, the transpiration rates do not vary greatly (Calder *et al*., 2003). The transpiration rates appear to be similar for coniferous and deciduous stand types, ranging from between 300-350 mm for a catchment receiving 1000 mm precipitation. However, coniferous woodland maintains high levels of evapotranspiration throughout the year, and including in the winter when most floods occur within the catchment.

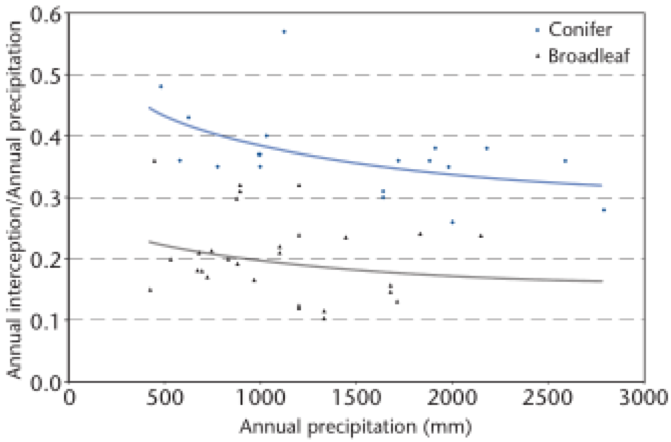

Figure 6.21. Percentage lost through interception (Forestry Commission, 2005)

Forests remove more water than non-forested land areas, though the difference will depend on the alternative tree cover, tree types and the management of trees (Table 6.6). Most studies have compared between the water use of forests and permanent vegetation (grassland, moorland) that is more likely to be converted to woodland (Robinson *et al*., 2003). Evapotranspiration rates for grassland fall within a range of 400 mm to 600 mm year^{-1} depending on the local conditions and the management regime. Heather moorland (*Calluna*, *Erica* spp.) has an interception loss between 16-19% and a transpiration potential between 20-42% (Calder, 1990). Hall *et al*. (1996) found that total evapotranspiration rates for crop systems range between 370-430 mm (from a total of 1000 mm rainfall) depending on the management of arable crops and irrigation works. Whilst the transpiration rates of growing crops exceed those of most trees, the overall loss is limited by short growing cycles.

Table 6.6. Percentages of annual evaporation losses typical ranges for different land covers (adapted from Forestry Commission, 2005)

Land cover	Transpiration (%)	Interception (%)	Total evaporation (%)
Coniferous	30-35	25-45	55-80
Deciduous	30-39	10-25	40-64
Grassland	40-60	-	40-60
Heather	20-42	16-19	36-61
Arable	37-43	-	37-43

The evapotranspiration rates calculated with the WaSiM-ETH model (Figure 6.22) fall within the expected rates based on previous studies. The average evapotranspiration rate for full afforestation with coniferous trees is c. 620 mm year^{-1} whilst for the deciduous layout is c. 450 mm year^{-1}. The mean annual precipitation for the baseline data used to drive the afforestation scenarios is c. 800 mm so the evapotranspiration rates are c. 55% for deciduous and c. 75% for coniferous stand types.

The average evapotranspiration for the 'No woodland' layout is c. 300 mm which represents c. 40% of the total rainfall. The value seems to be at the low end of the evapotranspiration potential for grassland (cf Table 6.6), however the catchment is more than 30% arable and 10% heather, vegetation types which have lower evapotranspiration rates and will in combination decrease the overall evapotranspiration rate.

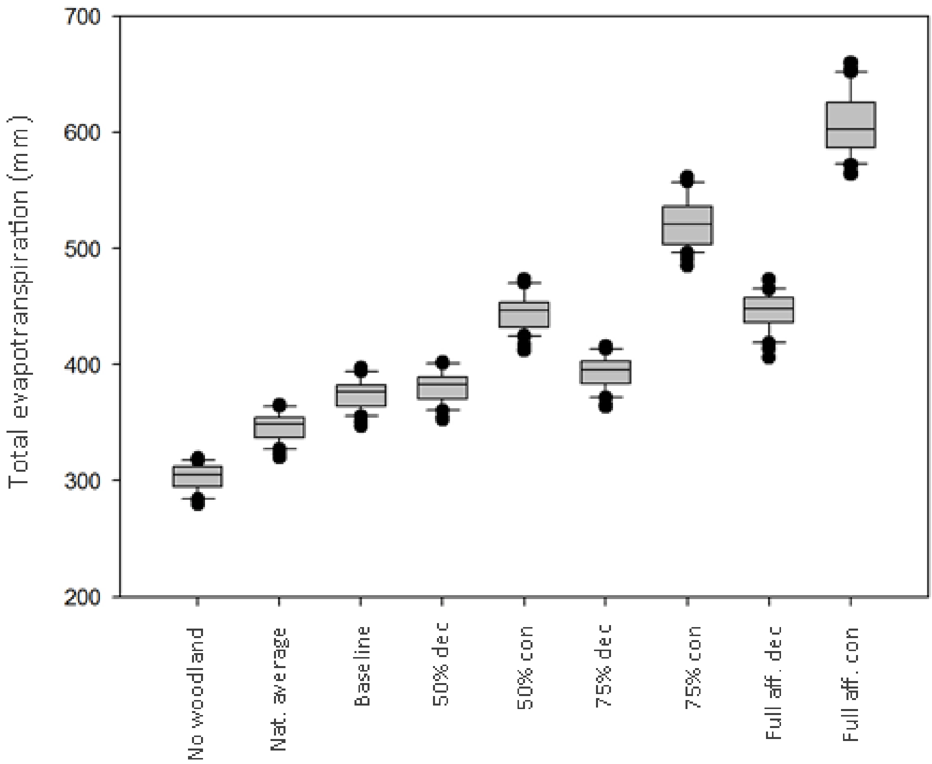

Figure 6.22. Total annual evapotranspiration for the baseline and the afforestation options

Figure 6.23 illustrates the annual average percentage increase of evapotranspiration for the afforestation layout over a 30 year period. It shows clearly that the difference in the Q_5 between different levels of afforestation is closely linked to the difference in the evapotranspiration rates.

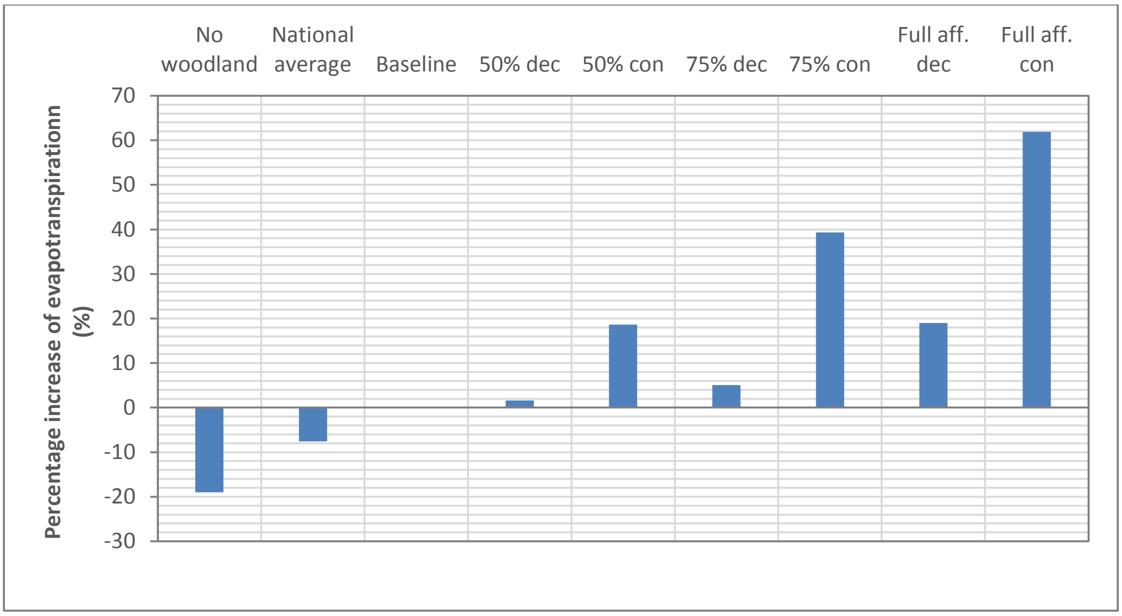

Figure 6.23. Average percentage increase from the baseline in the total evapotranspiration rate for the afforestation layouts

6.3.2.2 Low flows

Having established that increasing the forest cover in the Tarland Burn catchment reduces the high flows, it can also be shown to exert a significant impact on the low flows (see Table 6.7, Figure 6.24). This impact is well marked for larger values of afforestation though again varies across different woodland types (i.e. deciduous and coniferous). The decrease in low flow ranges between 33% for deciduous to more than 70% for coniferous if full afforestation is achieved in the catchment. If only 24% of catchment is afforested (50% woodland layout), the Q_{95} will drop by c. 3% for new deciduous woodland to c. 25% for new coniferous woodland. An afforestation level consistent with the National average scenario of 17% will lead to an increase of c. 10% in the Q_{95} in Tarland. In a scenario with no woodland in the catchment, having been replaced by grassland, the low flows would be up to 25% higher.

Table 6.7. The Q_{95} levels and percentages change from the baseline for the afforestation layouts

	Q_{95} (m^3/s)	Percentage change (%)
No woodland	0.3109	24.56
National average	0.3006	9.62
Baseline	0.232	0
50% deciduous	0.282	-3.30
50% coniferous	0.151	-25.46
75% deciduous	0.208	-9.41
75% coniferous	0.075	-51.29
Full afforestation deciduous	0.341	-33.13
Full afforestation coniferous	0.387	-75.99

Baseflow levels decline over time, as forest interception and transpiration rates increase. Experimental soil measurements indicate drier soil conditions under forest land cover, compared to nearby grassland (Robinson *et al*., 2003). As a result there will not be enough soil moisture to yield a normal level for the baseflow in dry weather periods, and the rewetting of the soil in autumn will be delayed. Since reductions of 7% or more are possible for every 10% of an aquifer where conifer replaces grass or arable land, large-scale planting of new conifer woodland should be avoided within areas of low water availability (Nisbet *et al*., 2011).

High levels of evapotranspiration have been noted to have a significant impact on the low flows for paired catchment studies undertaken in Australia, New Zealand and South Africa (Lane *et al*., 2005). At Lamrechtsbos and Biesvievley, the low flow reduction was 78% to 62% respectively, whilst at Redhill a reduction of 100% was measured for coniferous afforestation (Lane *et al*., 2005).

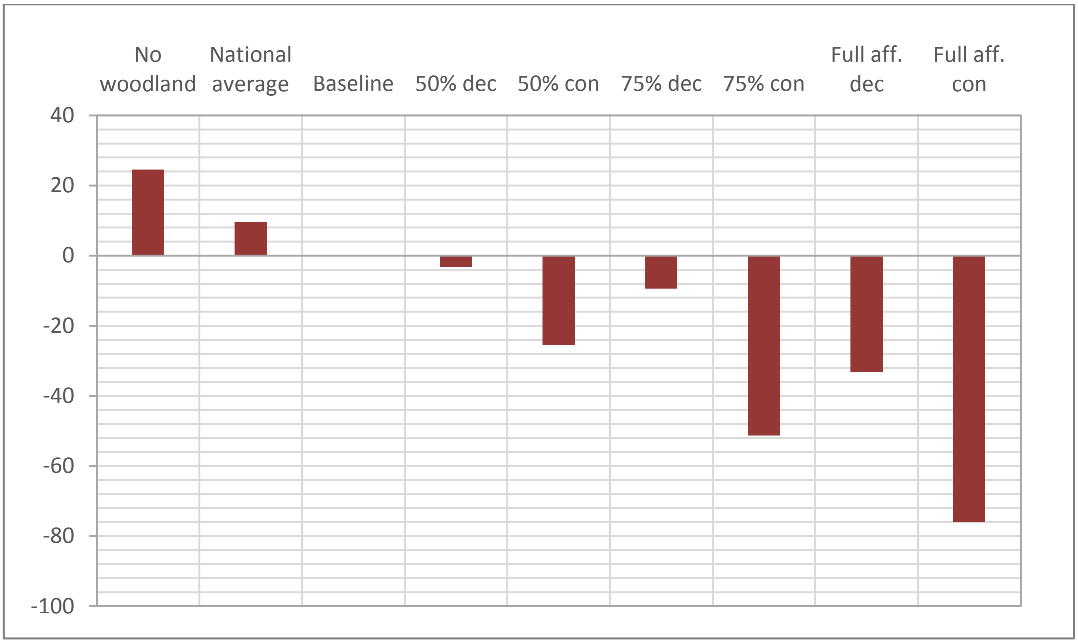

Figure 6.24. Percentage decrease of the Q_{95} from the baseline

These results have substantial implications for Tarland where droughts and low flows are already seen as potential issues. The water quality in Tarland is severely compromised due to diffuse pollution and morphological alteration (SEPA, 2013). Extended drought periods will also potentially impact a large number of remote dwellings and farmhouses that are relying on private water supplies. Moreover, lower water levels over the summer will lead to a rise of pollutant concentrations in the stream due to the lower dilution potential. This will have a direct impact on habitat availability and biodiversity (The Macaulay Institute for Soil Research, 2009).

Similar to the high flows, the results suggest that there are no significant differences in the low flow for the variants of the 50% and 75% scenarios (Figure 6.25). However, as previously discussed, this is explained by the similarity between the maps resulting from restrictions set in LandsFACTS.

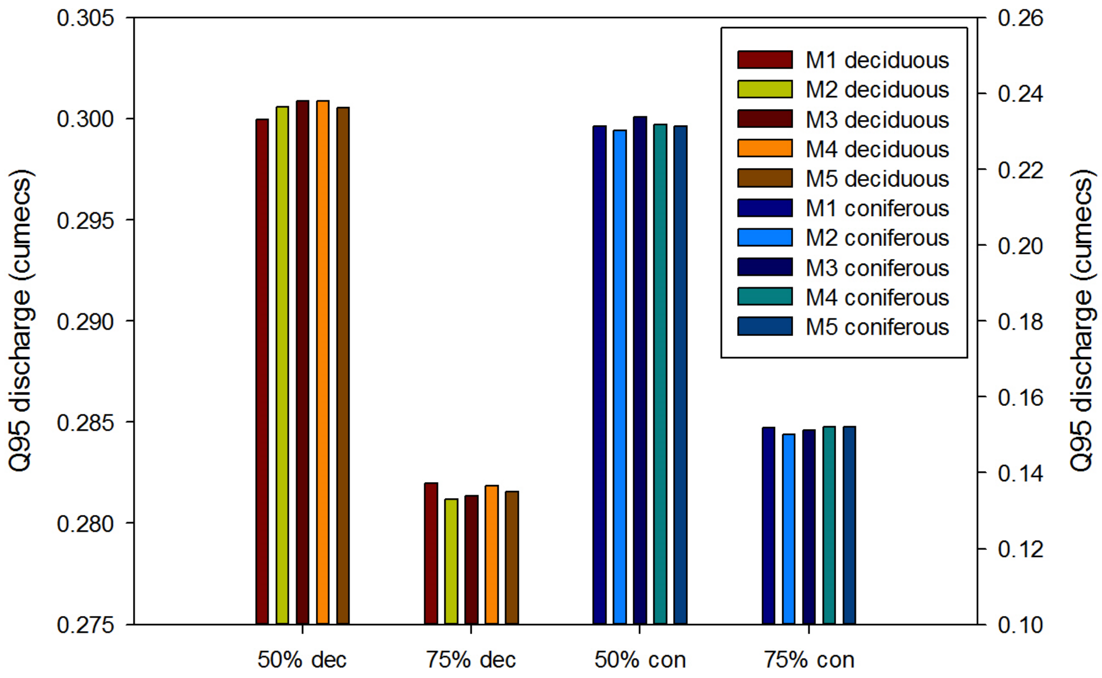

Figure 6.25. The difference between different realizations of the 50% and 75% afforestation levels with coniferous and deciduous woodland for Q_5

6.3.2.3 The impact of location

To test whether the location of afforestation has an impact on its effectiveness, in reducing the flood risk and in exacerbating drought phenomenon, two afforestation layouts were developed with a 10% increase of woodland located as follows: (i) upland replacing predominantly shrub and small percentages grassland and (ii) lowland replacing predominantly arable and small percentages of grassland. The maps used for this analysis are presented in Figure 6.26.

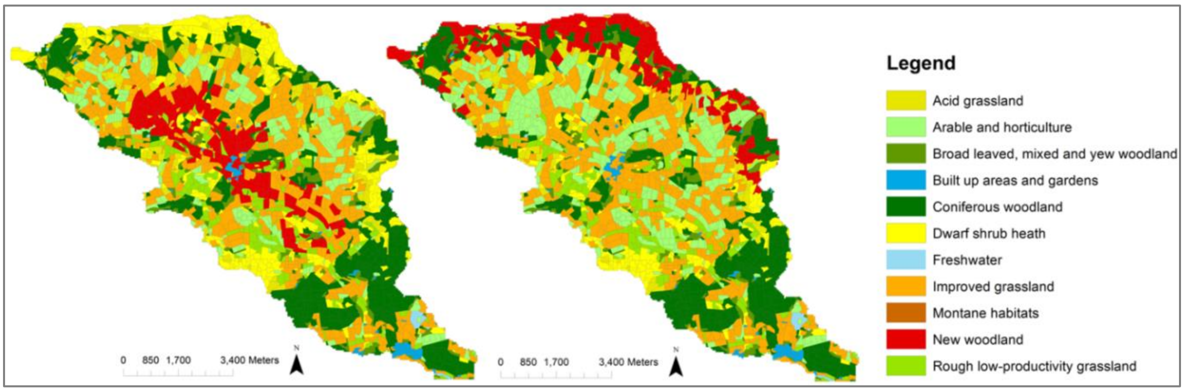

Figure 6.26. Maps with 10% afforestation used to test if location has an impact on how the discharge is affected

The results suggest that there is an important difference between the discharge reduction that could be achieved for afforested lowlands compared to uplands (Table 6.8).

Table 6.8.The levels of Q_5 and Q_{95} for the lowland and upland 10% afforestation level

	Current land use	10% lowland con	10% lowland dec	10% upland con	10% upland dec
Q_5	1.93001	1.77166	1.91083	1.82503	1.92682
Q_{50}	0.73988	0.68697	0.73346	0.69463	0.73768
Q_{95}	0.46689	0.43131	0.45971	0.43661	0.46477

The impact on the Q_5 is greater by a third for the lowland coniferous woodland compared to upland coniferous woodland (see Figure 6.27a). For deciduous woodland the difference is even greater (80%), though the overall reduction achieved by the deciduous woodland is considerably less compared to coniferous plantings. Hence, despite the large difference, the overall potential of lowland deciduous woodland to reduce the Q_5 is 8 times less than that of lowland coniferous and 5 times less than that of upland coniferous woodland.

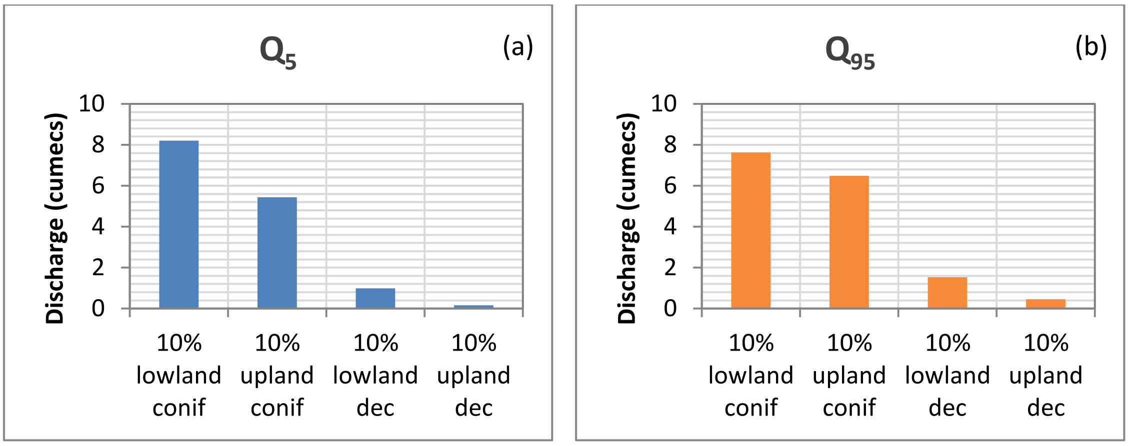

Figure 6.27. Percentage change from the baseline for lowland and upland 10% afforestation layouts for (a) Q_5 level, (b) Q_{95} level

The Q_{95} will be impacted to a lesser extent by the location (Figure 6.27b). The lowland coniferous stands would decrease the Q_{95} by an additional 15% compared to upland coniferous stands. For deciduous plantings, the difference would be a c. 70% reduction for lowland deciduous woodland compared to upland deciduous woodland. Whilst the results evidence that location influences the efficiency of afforestation options in reducing the high flows, they may also represent to some extent the difference between the land cover that is being replaced in the upland and lowland environments.

6.3.3 Assessment of socio-economic scenario

Figure 6.28 illustrates the FDCs for the socio-economic scenarios expressed as land use changes. The curves reveal relatively little difference between the future periods compared to the baseline (data of 1961-1990).

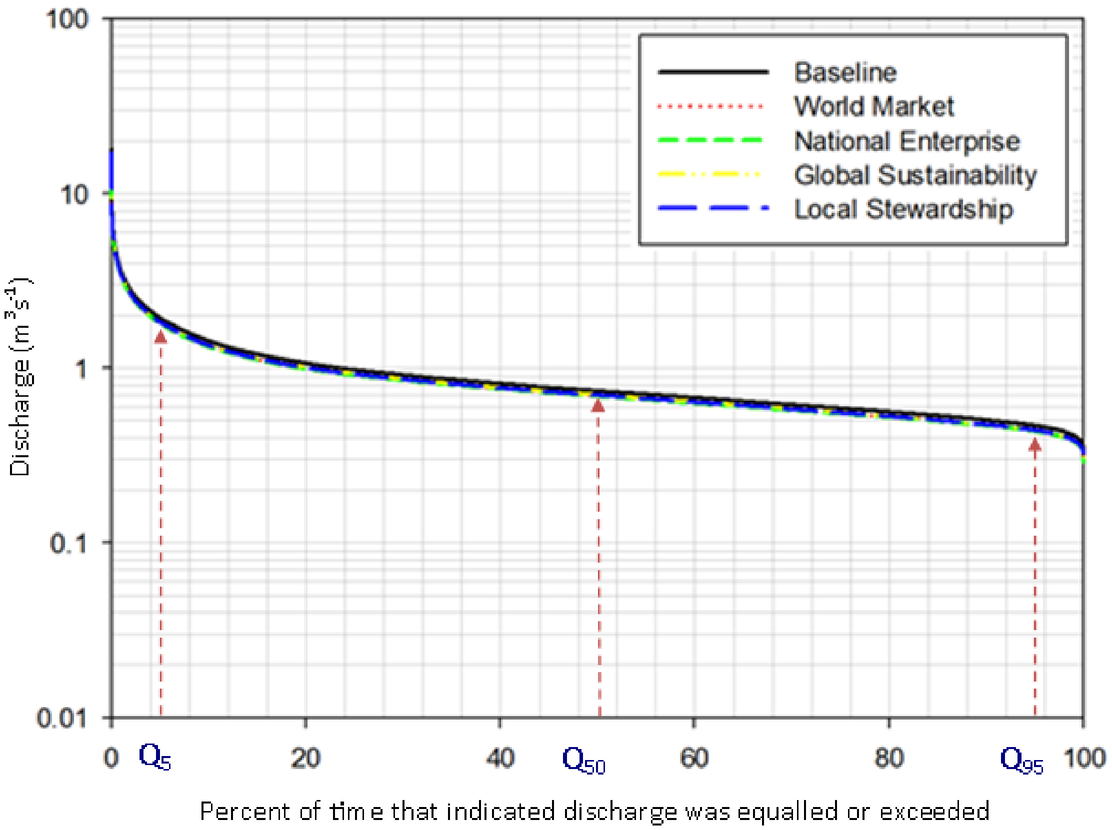

Figure 6.28. FDCs for socio-economic scenarios

The results for the socio-economic scenarios indicate that the National Enterprise scenario leads to the highest percentage decrease of the Q_5 relative to the baseline (Figure 6.29). The World Markets scenario decreases the Q_5 only 1% less than the National Enterprise scenario. For the Global Sustainability and Local Stewardship scenarios the Q_5 is decreased with similar values of c. 5%. The percentage decrease of Q_5 for Global Sustainability and Local Stewardship scenarios are lower than for the World Markets and National Enterprise scenarios, even though they have significantly higher levels of afforestation than the latter (21% new woodland compared to 4%). However the new woodland added in the catchment is deciduous for the Global Sustainability and Local Stewardship, and coniferous for World Markets and National Enterprise scenarios. As previously discussed, coniferous woodlands have higher levels of interception and evaporation making them more efficient at reducing the high flows compared to the deciduous woodland. Moreover, the new woodland for World Markets and National Enterprise scenarios is located in the lower part of the catchment, which would increase the effectiveness by which coniferous woodland reduces the Q_5 by up to 150% as demonstrated in section 6.3.2.3.

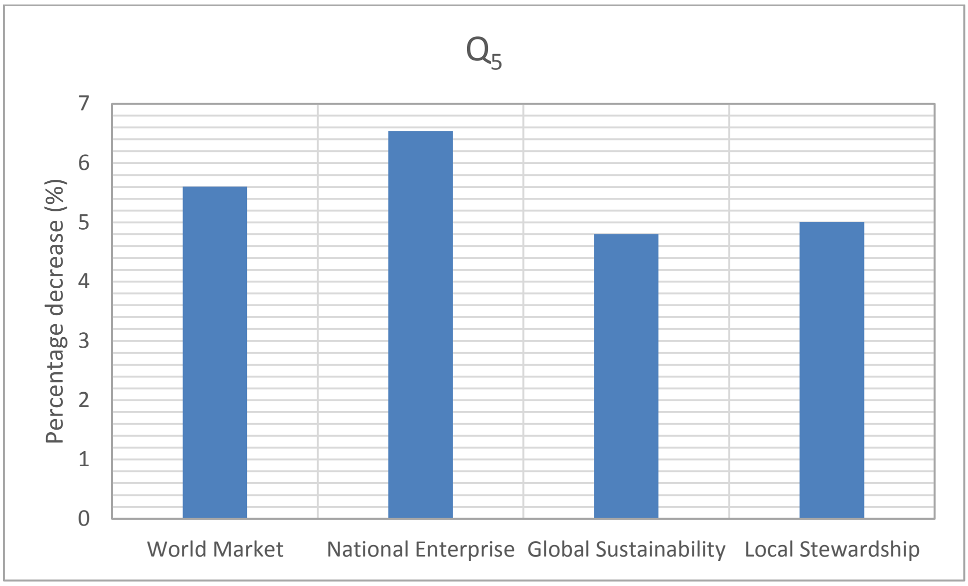

Figure 6.29. Percentage decrease from the baseline of the Q_5 for the socio-economic scenarios

The results suggest similar levels in terms of a percentage decrease for Q_{95}. The National Enterprise scenario would generate the highest percentage Q_{95} decrease with the World Markets, Global Sustainability and Local Stewardship scenarios at similar levels, i.e. c. 6% decrease (Figure 6.30).

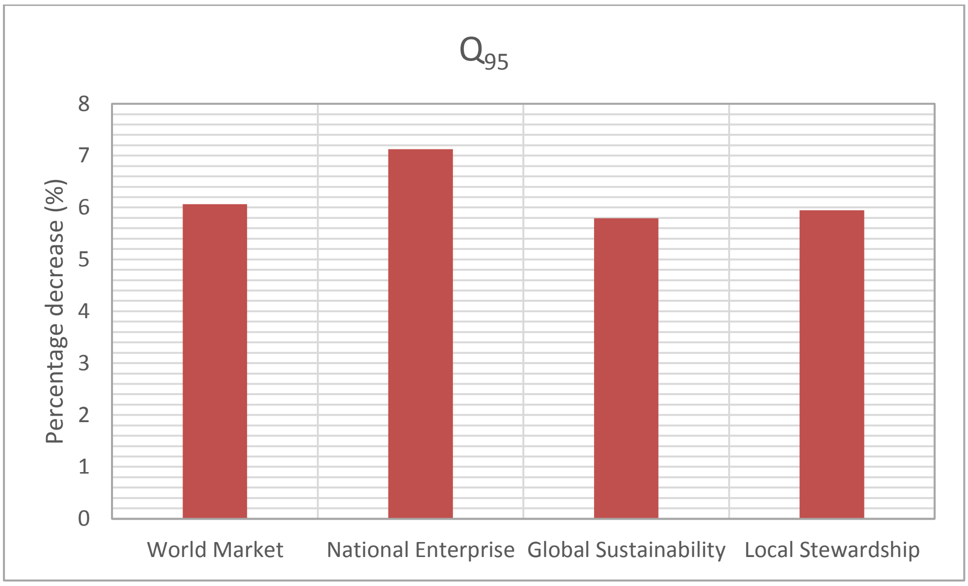

Figure 6.30. Percentage decrease from the baseline of the Q_{95} for the socio-economic scenarios

The overall impact of the socio-economic scenarios on both the Q_5 and Q_{95} is driven by the type of woodland used for afforestation, where the new woodland is located, and the land use type that is converted to woodland.

6.4 Discussion

Model results suggest that improved drainage has the potential to reduce the flood risk by increasing the soil storage capacity. Drainage systems with small distances between the drains could increase soil water retention while systems with larger distancing between drains could perform more poorly in draining the water out of the catchment. A similar result was described in a study from Germany which assessed the impact of drainage densities on rainstorm flood control (Wiskow & Ploeg, 2003). However the impact of improved drainage depends on the antecedent conditions and the flow components contributing to the runoff generation. A comprehensive study by Robinson (1990) showed that at the field scale, drainage generally decreased the flood peaks in areas where the water table was formerly high. If the ground water table is deeper and rarely contributes to surface runoff, flood peaks following drainage could increase as the subsurface flow paths are shortened.

The results for Tarland suggested that improved drainage density was more efficient at reducing the flood peaks in the summer than in the winter with a comparable effectiveness for different rainfall event magnitudes. As most flooding events occur in the winter in Tarland, the benefits of improved drainage become marginal, at just 2 to 5%. Early historical accounts from the parishes in the Tarland catchment indicated that drainage had a positive impact on the flood risk. Statistical accounts in the catchment from the Tarland and Migvie parish and for Coull parishes in late 18th Century describe the catchment before drainage works were carried out as having frequent floods in the winter and during heavy rain and dry summers due to poor drainage. Latter accounts in 1845 talk about ‘great improvements’ in the catchment following drainage works and better water management and distribution (McKeen, 2013).

With land drainage implemented in the catchment two processes will occur: (i) increased flow as the drains carry the water more rapidly than the inherent subsurface flow through the soil and (ii) reduced flow as a result of the increased soil storage capacity, because of lowering of the water table. Fundamentally the overall response will be determined by the processes that exert the greatest influence in each catchment

(Blanc *et al*., 2012). The impact of land drainage is site specific and it will depend on the soil type, antecedent conditions, drainage density and geometry, drain and surface roughness and rainfall event (Ballard *et al*., 2010).

The second type of NFM measure investigated was afforestation options. The results of the modelling experiments demonstrated that there is potential for afforestation measures to reduce the flood peaks in Tarland. Mature trees have a greater water use than other vegetation types (Bosch & Hewlett, 1982; Kirby *et al*., 1991).

Trees have high interception and transpiration rates resulting in higher evapotranspiration rates compared to other vegetation. The percentages lost through transpiration by both types of forests have similar values for different event magnitudes (Forestry Commission, 2005), suggesting that the potential of afforestation to alleviate large flood peaks is determined primarily by its interception capacity. Significant reduction in the high flows of more than 60% could be achieved if extensive afforestation is applied in the catchment (Figure 6.16). Similar results have been suggested by other studies with runoff reductions of 50% for afforested grasslands by the tenth year and a 35% reduction for afforested shrublands at the same age (Farley *et al*., 2005). Fahey & Jackson (1997) reported a reduction in peak flows between 55 to 65% after 12 years since the catchment had been afforested with pine plantation from a baseline of tussock grassland (total afforestation of 67%). Recorded flow peak reductions in paired catchments ranged between 34% at Lambrechtsbos to 100% at Redhill (Lane *et al*., 2005). These large variations in the response were explained by tree age, rainfall total and type of trees (mixture of coniferous and eucalyptus and other species). Maximum runoff reductions can be expected between 15 and 20 years after planting, and runoff reductions will likely be larger and more sustained for some afforested land covers (e.g. grasslands) than others (e.g. shrubland) (Farley *et al*., 2005).

Complete afforestation is an extremely unlikely scenario as most catchments provide crop and livestock benefits contributing to the food security targets in Scotland. However by choosing coniferous woodland for afforestation in Tarland, significant reductions of Q_5 could be achieved even for smaller levels of afforestation. Location was shown to play an important role in the effectiveness of afforestation measures. Lowland coniferous woodland could reduce the high flows by up to a third more than upland coniferous stands, whilst lowland deciduous forest could see reductions of up to

70% more than in the uplands. This is however subject to the type of land cover which is being replaced, the soil type and rainfall event dynamics.

The primary purpose of most conifer plantations is timber production, though a few lowland stands may also have landscape and game functions. Most trees are harvested when they are 40-70 years old using various clear fell methods. Therefore, even though coniferous plantation could provide benefits for flood risk management, especially after 15-20 years when their canopy reaches a full closure (Nisbet *et al*., 2008), the plantation cycle means that these benefits are temporary. The hydrological response of the catchment after clear felling would not be necessarily the same as current levels, because deforestation and afforestation are not necessarily opposite and predictable processes (Robinson *et al.*, 1991). Coniferous plantations could be maintained for carbon sequestration purposes. However when coniferous woodland is 10 to 30 years old the trees are forming a dense canopy which prevents the light from reaching the forest floor. This results in a very sparse ground flora and an understory which is less beneficial for biodiversity (Barbier *et al*., 2008). Harvesting the trees but keeping the stumps could increase the land roughness, dissipate energy, slow floodwaters and reduce the potential for flood damage downstream, but the evapotranspiration effect will be reduced. However significant debris could block bridges and culvert openings, and may cause bank erosion impacting the flows.

The effects of afforestation on low flows may be even more important than the changes on the overall annual flow as the impacts were shown to be most pronounced in the summer when the water levels are already low and impacting on water users the most (Farley *et al*., 2005; Smith & Scott, 1992). The interception and transpiration rates are at their highest in the summer growing season, resulting in a decreased discharge to the soils and decreased low flows. If the forest prevents sufficient recharge in the winter to the drift and solid geology, then the low flows will be greatly impacted especially for very dry summers when low flows are sustained by supplies from these sources (Johnson, 1998). Using paired catchment approaches in a regional study Black *et al.* (1995) analysed the impacts of afforestation on Q_5 in the summer. The results demonstrated a negative trend for low flows (Q_{95}) for 11 catchments, with more than 10% woodland cover and a negative correlation of the Q_{95} with the percentage cover of forest.

The influence of hydrological regimes and associated characteristics on the functioning of aquatic and riparian organisms has been long recognized through different frameworks such as the ‘environmental flows’ (Acreman & Dunbar, 2004) and ‘natural flow paradigm’ (Poff *et al*., 1997). Both concepts highlight the need for maintaining or restoring the natural flow variability to protect native biodiversity and freshwater ecosystems. The decrease in the low flows with extensive afforestation threatens the optimum functioning of these ecosystems and should be carefully considered.

Low flows and annual flows are progressively reduced as the forest matures (Farley *et al*., 2005; Robinson *et al*., 1991). Several studies have shown that after the first 5 years since new woodland was established reductions in low flows will be recorded (Fahey & Watson, 1991; Smith & Scott, 1992b). The impact on low flows will be more pronounced for certain species; Farley *et al*. (2005) found larger reduction in the low flow with eucalyptus than for pines and other species.

Large percentages of afforestation will have a significant impact both on low flows and high flows in Tarland. However the afforestation potential will be subject to socio-economic pressures and policy targets. The model results for the socio-economic scenarios shows that by favouring intensive agriculture on the good quality land and planting woodland on lesser quality land (World Markets), reductions of up to 5% could be achieved with a low percentage of coniferous woodland. Similar results were found for the National Enterprise scenario, which promotes an increase of arable land and the same percentage woodland increase as World Markets scenario. The difference of 1% between these scenarios is due to the location of new woodland and the character of the land cover being replaced by woodland.

A higher degree of environmental protection and land use planning to maximize the use of resources in a sustainable way are key components of the Global Sustainability and Local Stewardship scenario, though for the latter the decisions are taken at a local scale. Both scenarios promote the use of deciduous woodland by up to 21% which will provide small benefits for the flood peaks of c. 6%; the small differences between these two scenarios is explained by the location of new woodland. The type of woodland being used is the key factor explaining the similar runoff response for different levels of afforestation for the World Markets and National Enterprise scenarios (21%) and Global Sustainability and Local Stewardship scenarios (4%).

Afforestation with coniferous stands as previously discussed has considerably higher levels of runoff reduction compared to deciduous woodland. By using coniferous trees for woodland expansion in the catchment, important benefits could be achieved for flood risk protection. However more grants were given for deciduous woodland afforestation from 2000 to 2008 by the Forestry Commission (Forestry Commission, 2009). Whilst deciduous woodland could be beneficial for flood protection, the benefits are significantly less compared to those of coniferous woodland.

The results show that afforestation will not only decrease the high flows but also the low flows, potentially exacerbating drought issues that may already be present in the catchment subject to the afforestation percentage and tree type. This suggests that there is a trade-off that should be considered in the decision making process when woodland expansion is at a planning stage.

It must be noted that pre-afforestation drainage was not included in the model. Pre-afforestation drainage has been a common practice in reducing the water table between ditches, increasing aeration and improving nutrition (Johnson, 1998). The impact of drainage on runoff characteristics has been reported to increase the baseflow by up to 10-15% or in the case of upland catchments with very low baseflow to even double it (Robinson *et al*., 2003). The overall impact on baseflow in the initial stages of an operational phase will depend upon the balance between the interception and transpiration losses and the effects of drainage enhancements.

Moreover, in the model the forest was considered to be fully mature and at its highest potential for achieving runoff reductions. However afforestation measures will require a longer time to become efficient, which is especially important for flood vulnerable communities where there is a need to reduce the flood risk even for the current level of exposure. Other measures that have a lower lag time might need to be considered when an immediate decrease of flood risk is required.

6.5 Summary

Two NFM options have been modelled and the results are presented in this chapter along with a discussion of their overall performance. The impact of land drainage on peak flows is acknowledged; however, the extent of any potential change is mixed and likely to be catchment specific. To test how improved drainage is impacting on the runoff response a sensitivity analysis of the parameter controlling the density of the drainage network has been conducted. Results have shown that improved drainage can decrease the flood peaks in Tarland, though the impact is more marked for summer events (reductions of c. 9% from the baseline) compared to winter events (reductions of up to 5% from the baseline). Most floods occur in Tarland in the winter, so the immediate benefits of drainage during an extreme weather event are relatively small.

Afforestation measures were analysed to assess their effectiveness in reducing the flood risk and to better understand what the key contributing factors and the adverse impacts are. Results have shown that afforestation measures have a significant impact on the hydrological behaviour of the catchment both on the high flows and on the low flows. Full afforestation with coniferous woodland could reduce the flood risk by up to 60%. However an equivalent level of afforestation with deciduous woodland would yield a smaller reduction of the Q_5 (only 20%) compared to coniferous stands. This difference in the response is due to variation between the evapotranspiration rates of coniferous compared to deciduous trees. Modelling results also showed significant reductions of the Q_{95} particularly for large afforestation levels with coniferous woodland (up to 75% for full afforestation). Deciduous woodland would have a less negative impact on the low flows, with estimated reductions at 33% of the full afforestation levels.

The potential for afforestation in the catchment ultimately will depend on socio-economic drivers. To explore possible futures based on different policy priorities, the impact on the hydrological response of the catchment was analysed for a set of four socio-economic scenarios. The scenarios are generated using coherent and complex story lines which determine the levels of afforestation and arable land protection in the catchment. Results have shown that greater reductions could be achieved for scenarios that favour the use of coniferous woodland even for low percentages of afforestation. Location and land use cover being replaced by woodland are responsible for the difference between scenarios given the same level of afforestation with (i) World Markets and National Enterprise producing larger differences in flows than (ii) Global Sustainability and Local Stewardship.

The results clearly indicate that afforestation options could be used to decrease the flood risk in the catchment for the current climate. However with the likelihood of extreme weather events predicted to increase in the future, it is important to understand how well these measures could perform in reducing the flood risk under changing climatic conditions. The next chapter will investigate the performance of the afforestation configurations and land use scenarios into the future using UKCP09 climate projections.

Chapter 7. Evaluation of afforestation options and land use scenarios with future climate projections

7.1 Introduction

The performance of different afforestation options in reducing the flood risk based on current level of exposure has been demonstrated and discussed in the previous chapter. The effectiveness of such measures in Tarland is influenced by woodland expansion area (%), location and woodland type. However as more extreme weather events are projected to occur as a result of climate change, flood related issues are likely to intensify. In Scotland the agricultural land at risk of flooding is expected to increase up to 100% by the 2050s and by 170% by the 2080s from the current level if the current standard of engineered defences stays the same (Rowland & Fleck, 2012). The risk of inundation of residential properties could increase by up to 40% by the 2050s and by more than 60% by the 2080s (from the current number of ~50000) (Rowland & Fleck, 2012). The question remains as to how well NFM measures in the form of these different afforestation options will perform in reducing the flood risk into the future as the weather becomes more severe. To understand the effectiveness of the options as adaptation measures, model simulations were undertaken, initialized using the afforestation layouts and climate projections for 2020s, 2050s and 2080s. The simulation results were then compared with the baseline and are presented here along with an overall discussion of their performance.

As previously discussed in Chapter 6, any area of woodland expansion will depend on socio-economic pressures and biophysical conditions which will dictate the land available for new woodland planting. The four scenarios which provide plausible land use futures as defined in Chapter 6 have been compared to outline the types of change that will occur in land use by the 2050s, as a result of a change in the climate (e.g. warmer winter will lead to better agricultural yield). Climate projections for the 2050s from the Weather Generator have been used to drive the model and the simulation results are presented in this chapter.

7.2 Methodology

Different degrees of woodland cover were considered: 50%, 75% and full afforestation distinguishing between coniferous and deciduous woodland. The effectiveness of the afforestation options in reducing the flow peaks has been assessed for the UKCP09 (Murphy *et al*., 2009) baseline (1961-1990), 2020s, 2050s and 2080s medium emission scenarios to represent the conditions up to the end of the century. Four land use scenarios based on socio-economic factors have been investigated for the 2050s. The land use scenarios are plausible realisations of land use configurations accounting for the changes that will occur by the 2050s integrating a range of variables in a consistent and integrated manner (Brown & Castellazzi, 2014). As they are based upon the interaction of different socioeconomic and climate scenarios with soil and topographic conditions that influence local land use, they provide a more realistic (and complex) interpretation of future change than an arbitrary % change of woodland cover. The land use scenarios include potential changes linked to a warming climate notably an increased potential for agriculture, particularly in the middle region of the catchment which is expected to become prime agricultural land by the 2050s (Brown *et al*., 2008). As a result it suggested that it is highly unlikely that this area will be afforested because of its high value as farmland. A full description of the afforestation options and the land use scenarios was provided in Chapter 6.

Extreme rainfall events were calculated from the UKCP09 climate projections, using the Weather Generator and following the methodology described in Chapter 5. The calculated rainfall totals for 7 hour and 15 hour events were distributed into an hourly format using FEH design rainfall profiles (Institute Hydrology, 1999). The impacts of extreme rainfall events on the discharge were simulated using the WaSiM-ETH model calibrated for summer and winter months to simulate the dry and wet antecedent conditions. The rainfall events used for this analysis are provided in Appendix C.

7.3 Evaluation of afforestation options into the future

Table 7.1 presents the flow peaks for the afforestation options across two event durations (7 hour and 15 hour) and for different magnitude return period events (10-year and 100-year) for the baseline, 2020s, 2050s and 2080s (medium emission scenario).

Table 7.1. Peak flows (in m^3/s) for afforestation options for the baseline (1961-1990) and 2020s, 2050s, 2080s climate change scenario for the medium emission scenario

Climate scenario	Afforestation option	Summer 10 year return period		Summer 100 year return period		Winter 10 year return period		Winter 100 year return period	
		7 hour	15 hour	7 hour	15 hour	7 hour	15 hour	7 hour	15 hour
Baseline	Current land use	3.39	4.33	5.99	8.35	7.07	8.53	12.54	12.60
	50% con	2.74	3.53	4.89	6.92	6.29	8.01	11.44	11.93
	50% dec	3.30	4.19	5.82	8.12	6.99	8.49	12.33	12.53
	75% con	1.99	2.67	3.68	5.47	5.48	7.45	10.26	11.25
	75% dec	3.18	4.06	5.66	7.91	6.88	8.44	12.07	12.45
	Full aff con	1.15	1.63	2.23	3.55	4.40	6.72	8.74	10.29
	Full aff dec	2.41	3.15	4.33	6.13	6.31	8.06	11.22	11.94
2020s	Current land use	3.68	4.85	6.84	10.05	7.75	9.09	14.29	13.98
	50% con	2.98	3.97	5.60	8.43	6.88	8.55	13.07	13.26
	50% dec	3.58	4.72	6.65	9.78	7.66	9.05	14.01	13.89
	75% con	2.18	3.03	4.28	6.71	6.02	7.98	11.74	12.53
	75% dec	3.46	4.58	6.46	9.53	7.54	9.00	13.63	13.80
	Full aff con	1.29	1.87	2.59	4.46	4.88	7.21	10.03	11.52
	Full aff dec	2.63	3.53	4.95	7.50	6.88	8.60	12.64	13.26
2050s	Current land use	3.88	5.19	7.46	11.01	8.17	9.44	15.61	14.70
	50% con	3.14	4.27	6.11	9.27	7.27	8.89	14.27	13.96
	50% dec	3.77	5.05	7.25	10.71	8.08	9.39	15.25	14.61
	75% con	2.31	3.26	4.70	7.49	6.38	8.31	12.81	13.21
	75% dec	3.65	4.90	7.06	10.43	7.94	9.34	14.88	14.52
	Full aff con	1.37	2.02	2.88	4.98	5.20	7.51	10.95	12.18
	Full aff dec	2.79	3.77	5.41	8.25	7.26	8.93	13.65	13.96
2080s	Current land use	3.97	5.44	7.58	12.14	8.38	9.71	15.88	15.59
	50% con	3.22	4.47	6.22	10.26	7.52	9.13	14.52	14.80
	50% dec	3.87	5.28	7.38	11.80	8.28	9.66	15.74	15.49
	75% con	2.37	3.43	4.79	8.32	6.57	8.55	13.01	14.01
	75% dec	3.74	5.14	7.18	11.48	8.14	9.60	14.99	15.37
	Full aff con	1.41	2.13	2.93	5.55	5.36	7.72	11.14	12.94
	Full aff dec	2.86	3.95	5.50	9.08	7.44	9.17	13.87	14.78

The results show significant changes in peak flows for the afforestation options into the future. Model simulations suggest that increased afforestation will substantially decrease the peak flows in the summer whilst in the winter the impact will be less pronounced though still significant for some afforestation options (i.e. large percentage woodland expansion with coniferous trees).

Figure 7.1 presents the percentage change (%) of the flow peaks from the current land use for the baseline (1961-1990), 2020s, 2050s and 2080s for two event durations (7 hour and 15 hour event duration) across two design precipitation events (10-year and 100-year return period) for summer and winter antecedent conditions.

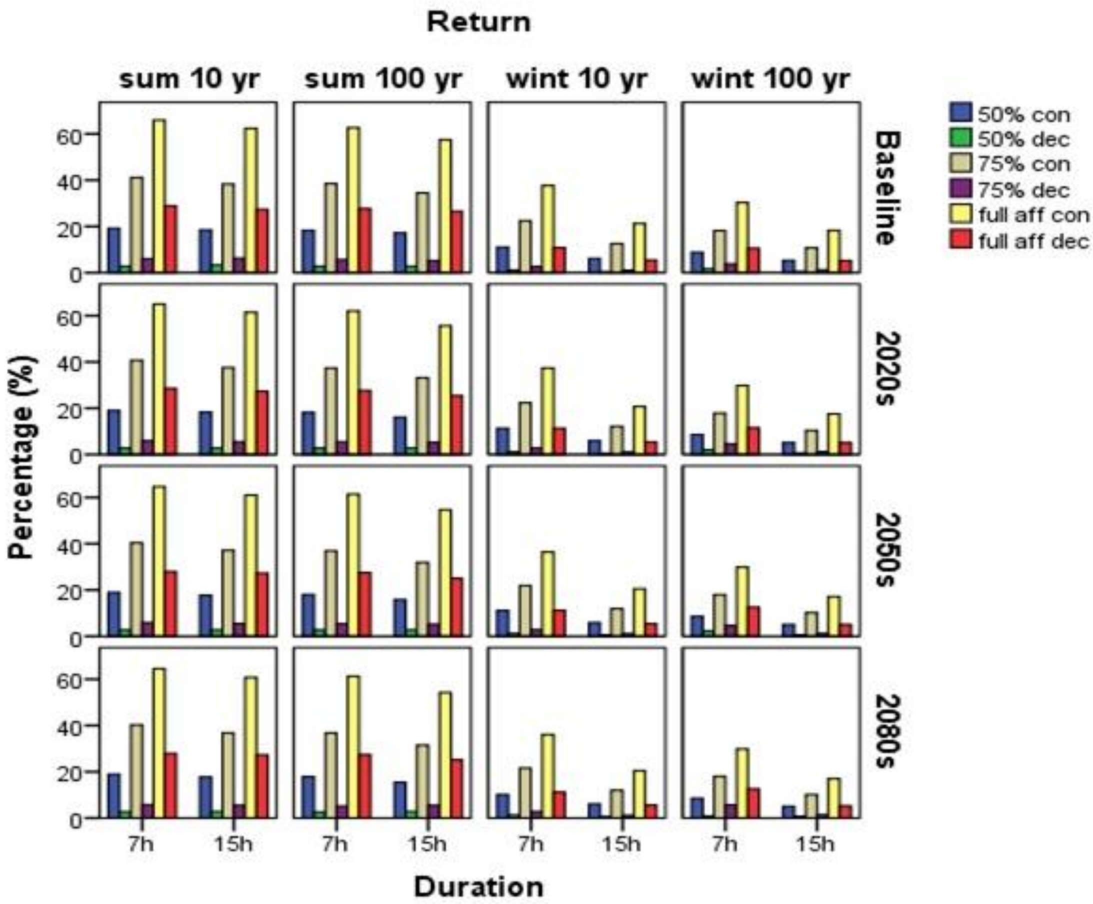

Figure 7.1. Percentages change (%) in the peak flow for the afforestation options for the baseline (1961-1990), 2020s, 2050s and 2080s

The results show that there is potential for the afforestation options to reduce the high flows under different climate projections; however their effectiveness will decrease as the magnitude of rainfall events and consequently floods increases in the future. The highest percent changes have been noted for summer events across different event durations and return periods. Full afforestation with coniferous woodland will generate the largest change of an c. 65% flow decrease from the current land use for the 2080s projections (for 10-year return rainfall event, summer antecedent conditions). However the peaks on which the greatest difference was noted are in-bank events of no more than 5.4 m^3s^{-1}. The results suggest that afforestation options could be more effective at reducing the flood risk for small magnitude events that occur following dry conditions.

As previously discussed in Chapter 5, under the UKCP09 climate projections, precipitation totals will increase, resulting in higher flow peaks assuming current land uses were maintained, but the decrease in the high flows achieved by woodland expansion will not completely counteract the climate change impacts. Consequently, whilst the afforestation options will decrease the flows into the future, the flood risk will continue to increase up to end of the century based upon these future projections. This is extremely important, as this implies that even if large afforestation percentages are achieved, this may still not provide a sufficient level of protection in the future. Other NFM and engineered measures may be required to alleviate the impacts of climate change in the catchment, e.g., through small-scale environmental engineering interventions (Nicholson *et al*., 2012; Wilkinson *et al*., 2010).

The analysis assumes the trees as fully matured. However even if the trees were planted today, their effectiveness in alleviating the flood risk would gradually increase up to the 2050s and 2080s when woodland would reach its maturity (average of 40 years for coniferous woodland and 60 years or more for deciduous woodland depending on the tree species (Archer *et al*., 2013).

Figure 7.2 presents the model simulations for the afforestation options for the baseline, 2020s, 2050s and 2080s, with summer antecedent conditions for 7 hour and 15 hour event durations, across two event magnitudes (10-year and 100-year return period).

Figure 7.3 presents the model simulations for the afforestation options for the baseline, 2020s, 2050s and 2080s, with winter antecedent conditions for 7 hour and 15 hour event durations, across two event magnitudes (10-year and 100-year return period).

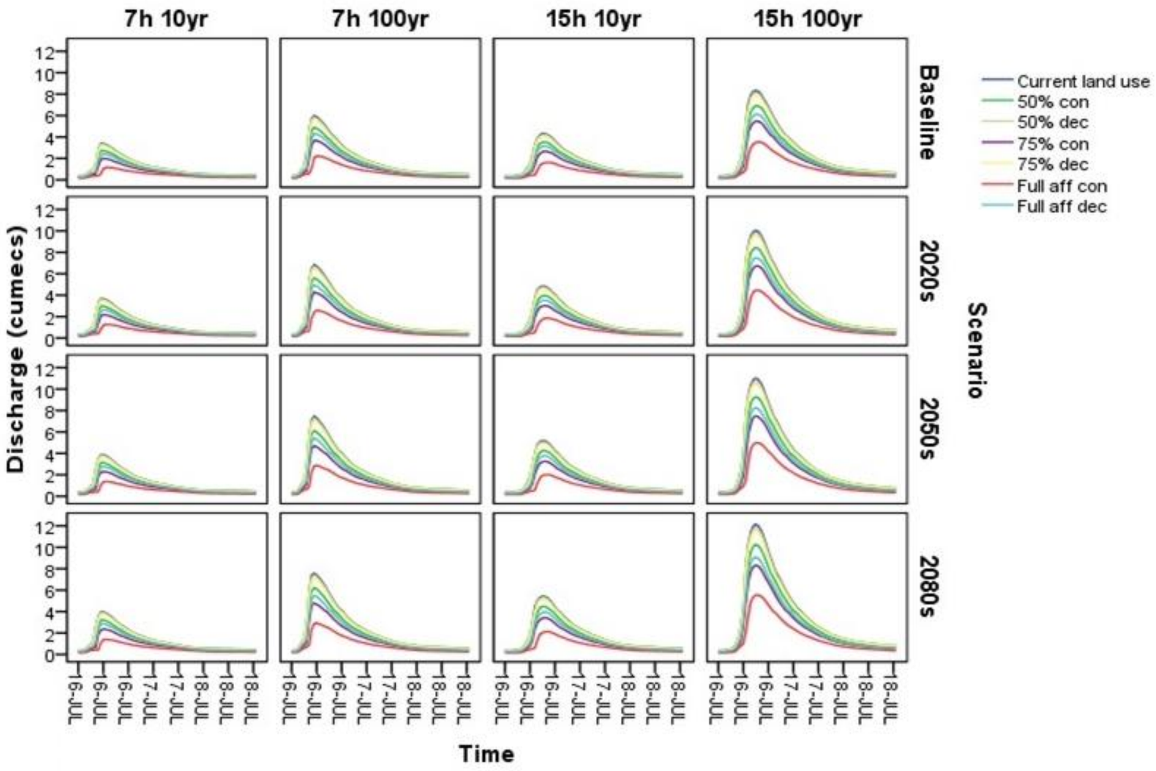

Figure 7.2. Modelling results for the afforestation options under different climate scenarios for summer events

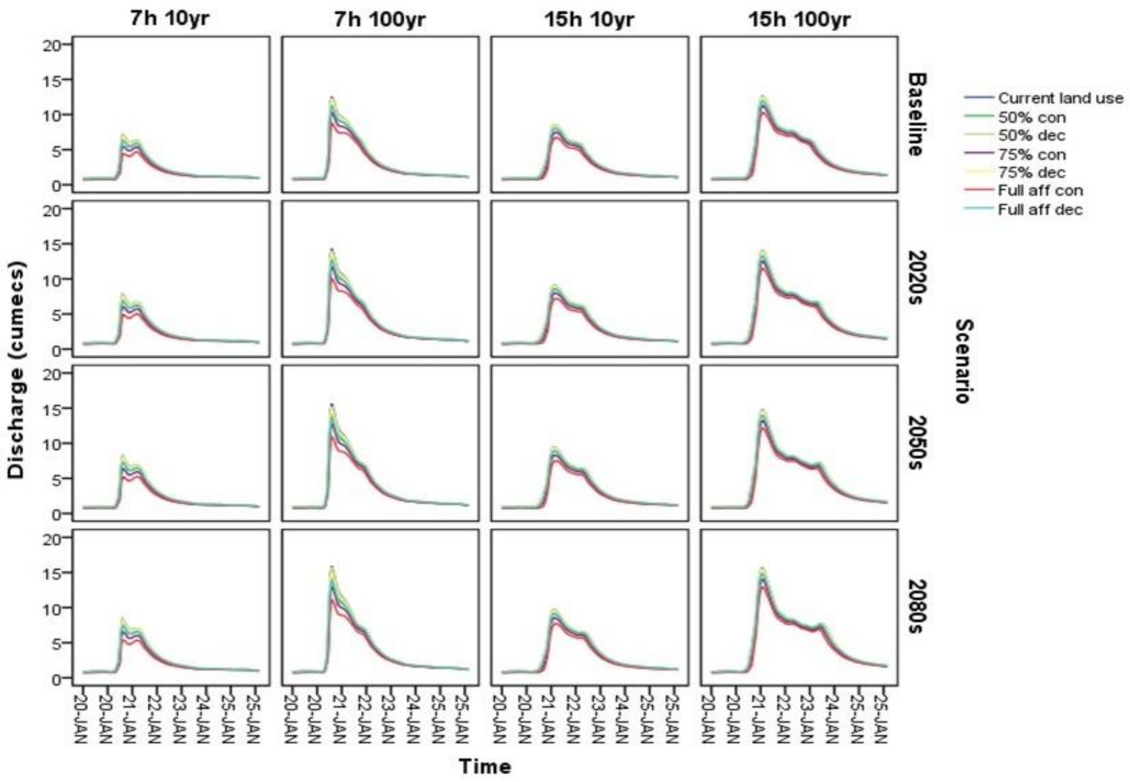

Figure 7.3. Modelling results for the afforestation options under different climate scenarios for winter events

Two graphs have been selected for a more in-depth discussion, to understand how the antecedent conditions may influence the impact that afforestation options can have on reducing the high flows by the 2080s. Figure 7.4 presents the results for summer events, for a 15 hour event duration, for a 10-year rainfall return period, for the 2080s.

Figure 7.4 illustrates that afforestation options have the potential to significantly reduce the flow peaks in the summer. Increasing the woodland cover to 100% could decrease the peaks by more than 3 m^3s^{-1}. Even lower percentages of woodland expansion could alter the flow peaks substantially. A 50% woodland cover could reduce the peaks by c.1 m^3s^{-1} (more than a 17% reduction from the baseline). The baseflow would be reduced significantly, which as previously discussed could exacerbate existing low flow issues within the catchment. This negative effect will be more apparent for large percentages of afforestation with coniferous woodland.

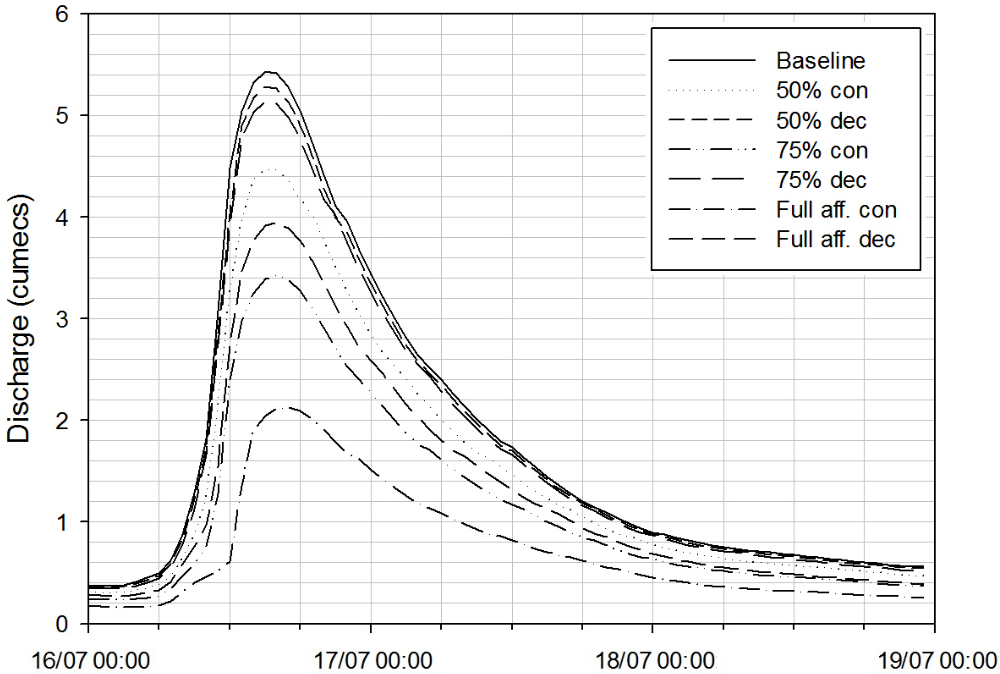

Figure 7.4. Modelling results for 15 hour event duration for summer antecedent conditions of a 1 in 10 year rainfall return period rainfall event under the 2080s medium emission scenario

Figure 7.5 presents the results for winter events for a 15 hour event duration for a 100-year rainfall return period event for the 2080s.

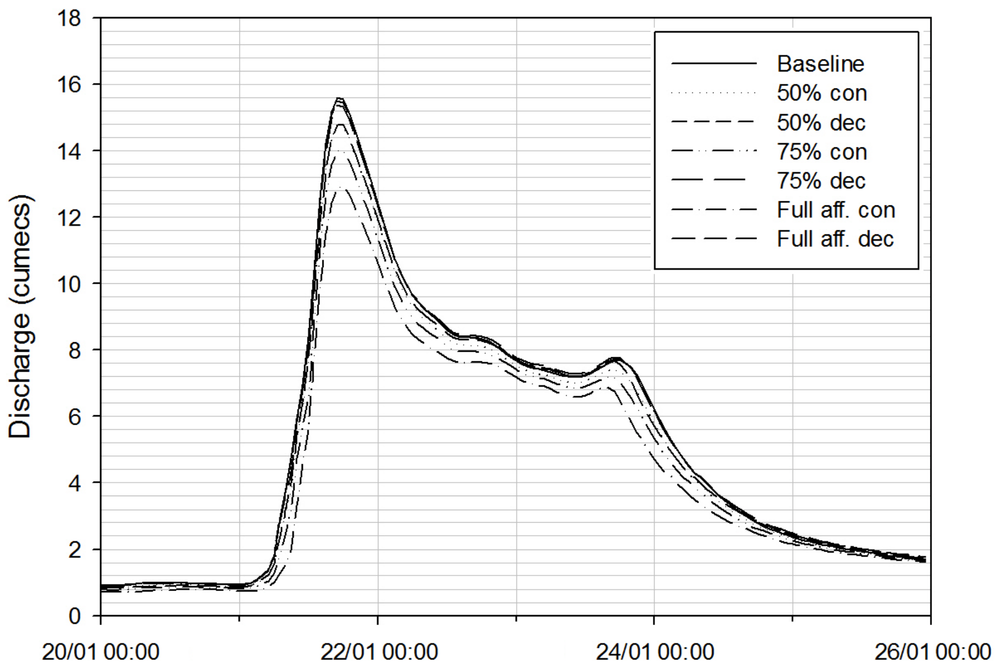

Figure 7.5. Modelling results for 15 hour event duration for winter antecedent conditions of a 1 in 100 year rainfall return period rainfall event under the 2080s medium emission scenario

The flow reduction that can be achieved for the afforestation options decreases in the winter as there is less capacity for woodland to divert precipitation through hydrological pathways other than runoff therefore the discharge generated is much higher. The available storage that can be accessed during a rainfall event are interception and soil storage (Shaw *et al*., 2011). Soil storage in the winter will be reduced due to high soil moisture and filled air pores. The interception capacity is thus limited to the vegetation cover, and it will decrease (as a percentage of the rainfall total) as the flood magnitude increases. Moreover the interception capacity will also decrease in the winter especially for deciduous woodland.

Another way in which afforestation can contribute to reducing the flood risk is by delaying the time to peak. Model simulations show that full afforestation with coniferous woodland increased the time to peak by 2 hours in the summer, and by one hour in the winter for smaller magnitude events (e.g. 1 in 10 year return period events, 15 hour duration). Time to peak is also predicted to lengthen for larger magnitude events (e.g. 1 in 100 year return period events) for long duration events (15 hour) by 1 hour. The 75% afforestation with coniferous woodland leads to a delay in the time to peak of 1 hour for low magnitude extreme rainfall events (1 in 10 years) over long durations. For a 1 in 100 years events the delay was only recorded for the baseline and the 2020s. The benefit of delayed time to flood peak is increased time for warning and preparation.

7.4 Evaluation of land use scenarios for 2050s

The land use scenarios were compared between the baseline (1961-1990) and the 2050s for 7 hour and 15 hour event durations, for summer and winter antecedent conditions. Figure 7.6 presents the results for the 7 hour event for summer antecedent conditions whilst Figure 7.7 presents the results for the 7 hour event for winter antecedent conditions. Similarly Figure 7.8 and Figure 7.9 illustrate the model simulation results for 15 hour events for summer antecedent conditions and for the winter antecedent conditions, respectively.

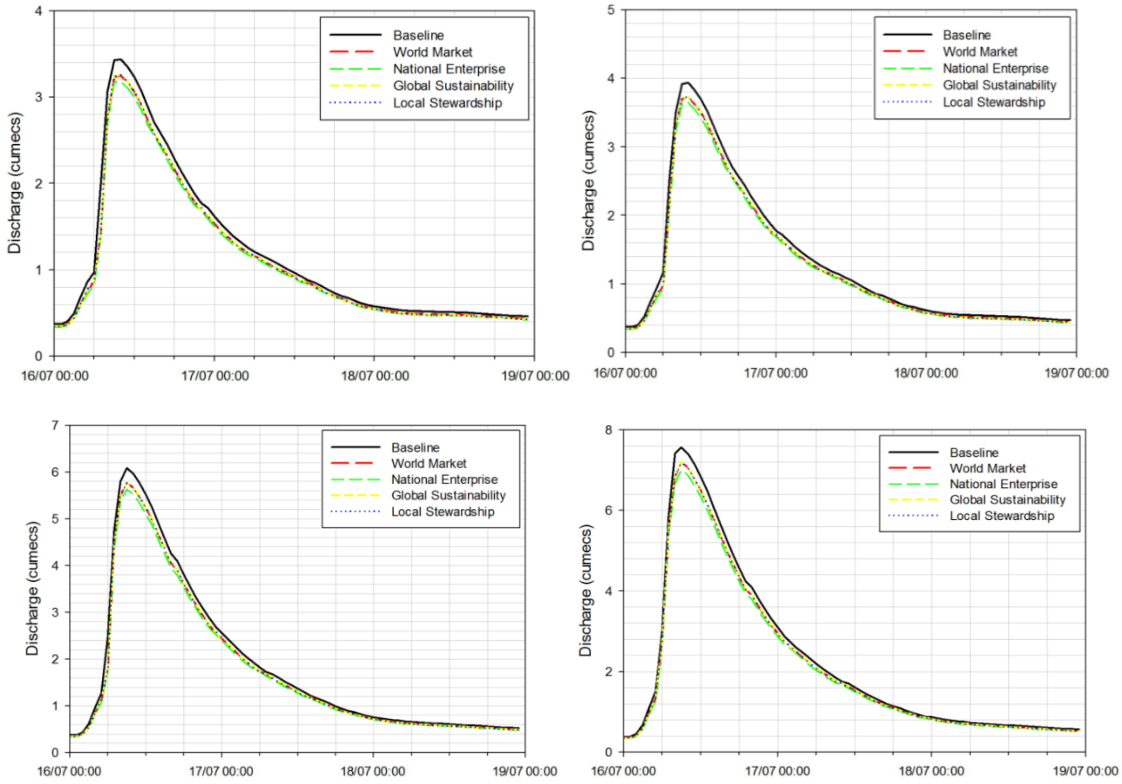

Figure 7.6. Model simulation results for 7 hour events with summer antecedent conditions for (a) baseline, 10 years return period event (b) 2050s, 10 years return period event (c) baseline, 10 years return period event, (d) 2050s, 100 year return period event

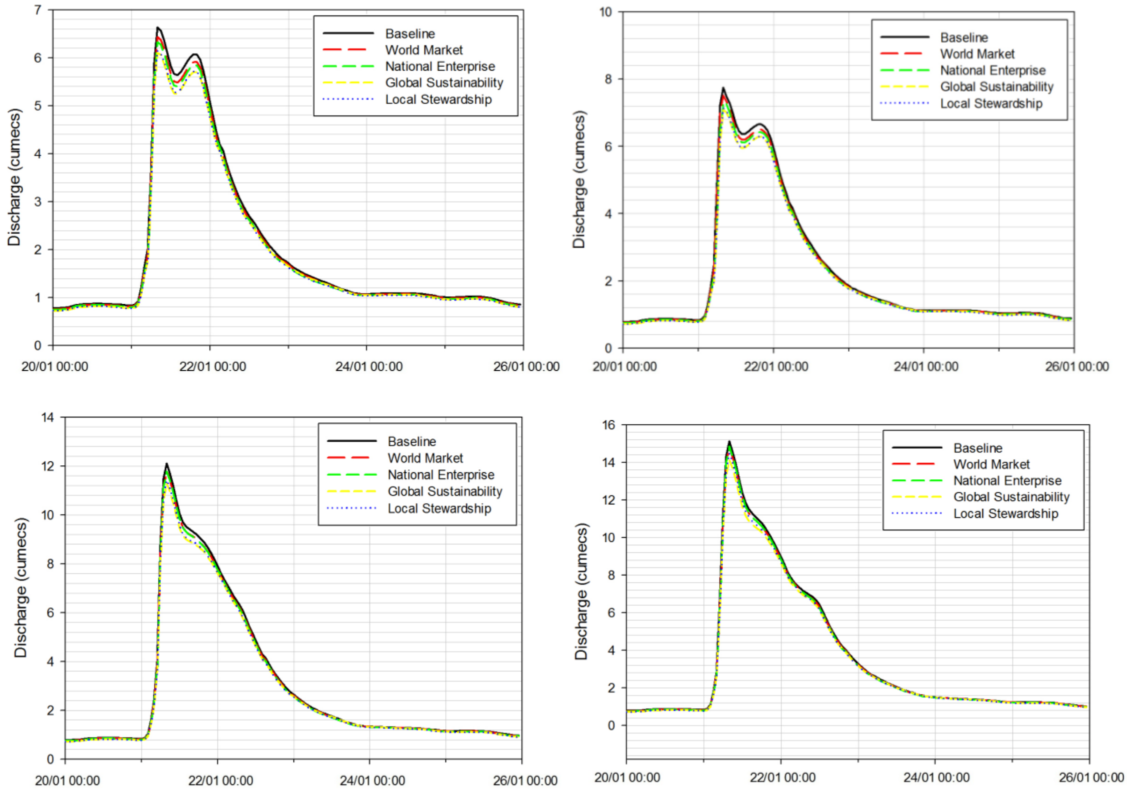

Figure 7.7. Model simulation results for 7 hour events with winter antecedent conditions for (a) baseline, 10 years return period event (b) 2050s, 10 years return period event (c) baseline, 10 years return period event, (d) 2050s, 100 year return period event

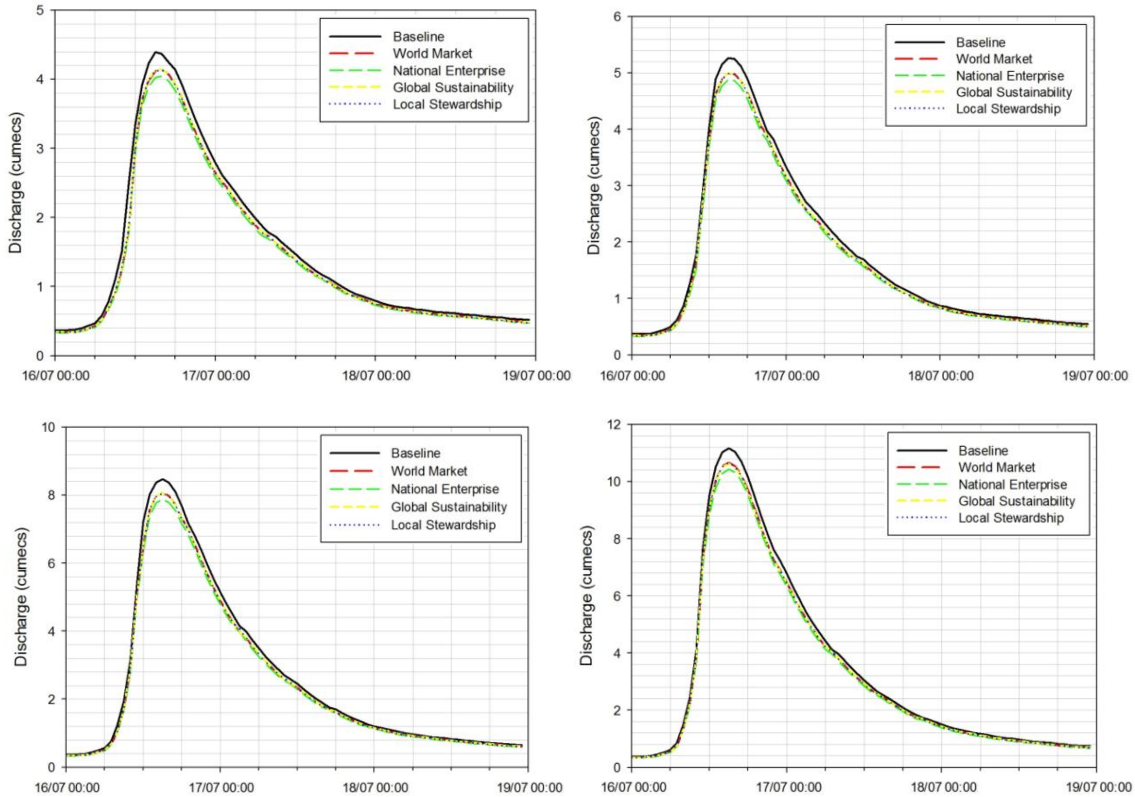

Figure 7.8. Model simulation results for 15 hour events with summer antecedent conditions for (a) baseline, 10 years return period event (b) 2050s, 10 years return period event (c) baseline, 10 years return period event, (d) 2050s, 100 year return period event

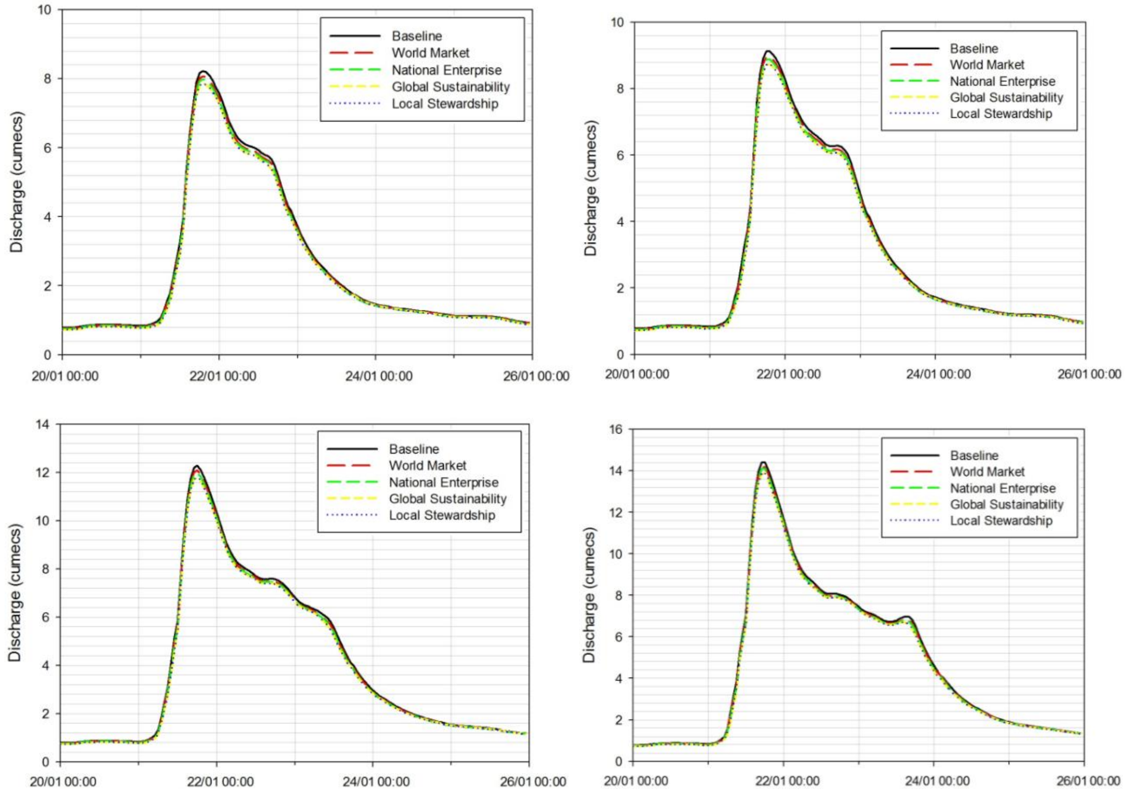

Figure 7.9. Model simulation results for 15 hour events with winter antecedent conditions for (a) baseline, 10 years return period event (b) 2050s, 10 years return period event (c) baseline, 10 years return period event, (d) 2050s, 100 year return period event

The results show a variation between the discharge response under the different land use scenarios, for summer and winter antecedent conditions. As expected based on the results from the afforestation increases, higher peak reductions are achieved in the summer. All scenarios recorded a percentage change from the current land use of more than 5% for summer antecedent conditions. The National Enterprise scenario recorded a larger peak flow decrease of c. 7%, which can be explained by the variation in the woodland location and the use of coniferous species for afforestation. For the winter, there were larger variations between scenarios World Markets and National Enterprise, achieving between 1.5-5% decrease, and Global Sustainability and Local Stewardship which decreased the peak flow by 3.5-8% from the baseline. The difference can be interpreted as a result of the significantly larger percentage of afforestation for the Global Sustainability and Local Stewardship scenarios compared to the smaller percentages of afforestation but this being of coniferous trees in the National Enterprise and World Markets. In the winter the soil storage will be limited so the interception will play a more important role, whilst in the summer the soil storage capacity will be more important in taking up excess water.

The difference recorded for the winter events between the scenarios is larger than the one previously noted for Q_5. This is due to an averaging effect when calculating the Q_5 using a long time series (30 years) and it draws attention to the importance of antecedent conditions when assessing the effectiveness of afforestation options for specific extreme rainfall events.

Figure 7.10 presents the percentage change from the baseline of the peak flows, for 7 hour and 15 hour events, under summer and winter antecedent conditions.

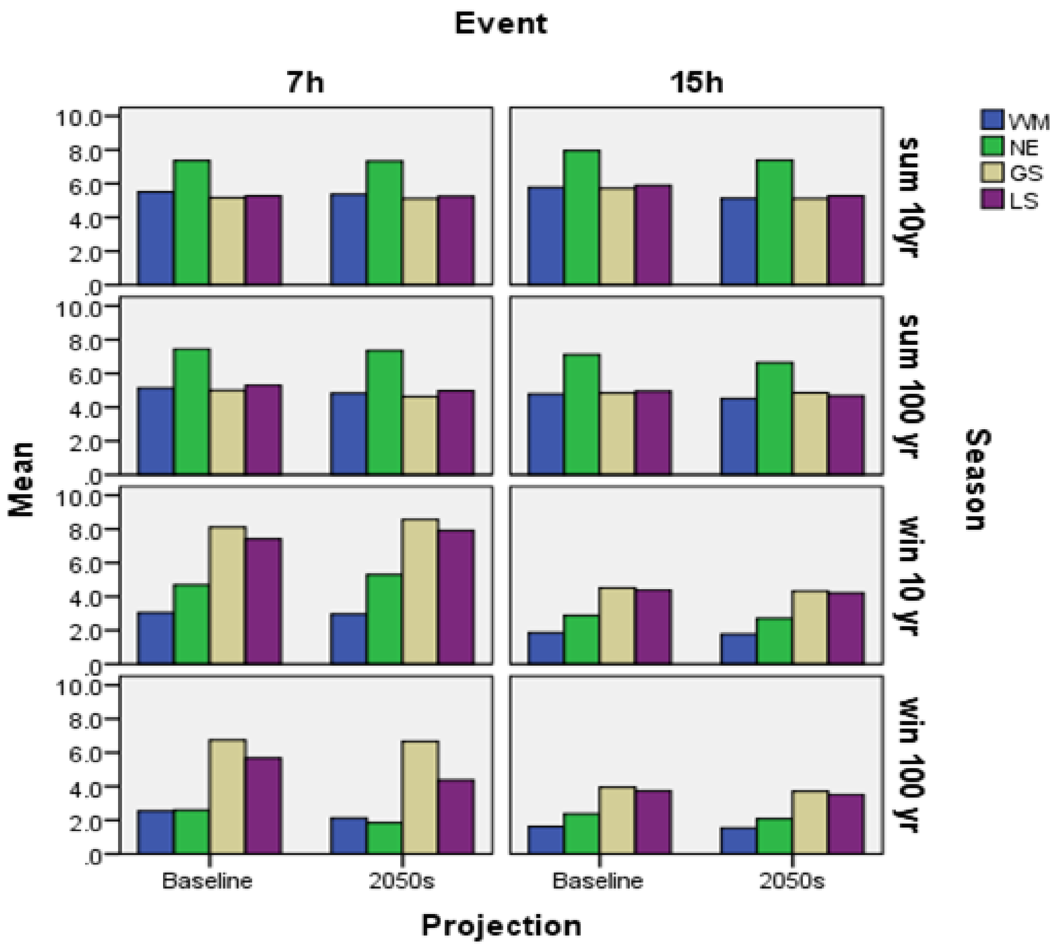

Figure 7.10. Percentage change from the baseline (%) for the land use scenarios

As expected, the land use changes associated with the land use scenarios have a higher impact in the summer as the evapotranspiration rates and the soil storage are increased. In the winter, the percentage change from the baseline is reduced especially for the World Markets and National Enterprise scenarios. This may be due to reduced evapotranspiration rates but an increase in the importance of below ground mechanisms for water storage i.e. increased infiltration rates, preferential pathways for water flow for the overall water loss. As World Markets and National Enterprise imply an afforestation of only 4% compared to 21% for deciduous in the other two scenarios, the overall loss in the winter will be smaller for these scenarios.

Climate change will increase the flood risk for the current land use by the 2050s, and so the benefits for flood risk achieved under different land use scenarios will become marginal compared to the expected level of exposure. Therefore, the overall flood risk is expected to increase by the 2050s unless the proposed levels of afforestation are increased to a higher rate as represented by the woodland expansion testing in section 7.3.

7.5 Discussion

The results suggest that afforestation options can play an important role in regulating flow into the future. Significant high flow reductions could be achieved for high levels of afforestation with coniferous tree species. The peaks could be reduced by up to 65% in the summer and 36% in the winter (for a 10 year rainfall return period event) compared to the current land use for the 2080s assuming full afforestation. To maximize the effectiveness of woodland, the species choice will be an important factor to consider (Nisbet *et al*., 2011). In Tarland catchment coniferous woodland could decrease the high flows significantly (for a high percentage of woodland cover), however it could cause a reduction in groundwater recharge and decrease the river flows, exacerbating existing water quality issues in the summer (The Macaulay Institute for Soil Research, 2009). This is particularly important to consider as warmer and drier summers are projected not only for the east of Scotland but also elsewhere in the UK. Moreover during dry summers water demand already exceeds supply in the south and could rise by up to 27% by 2021 (from 1990s level) (National Rivers Authority, 1994). Species selection is key in addressing the climate change impact on water supplies in regions where drier summers are expected (Calder *et al*., 2003; Nisbet *et al*., 2011). Planting higher yielding species (such as Eucalyptus or southern beech) could have major impacts in areas where the rainfall is no more than 800 mm. A study by Calder *et al.*, (2009) showed that native ash enhanced the water yields by 1.5-20% per 10% cover from grass by the 2080s (based upon UKCP02), making it an attractive option for climate change adaptation.

The impact that climate change will have on Scottish woodland is uncertain. Warmer temperatures may provide suitable conditions for tree growth (including changes in the effect of competing species) and increase the timber yields (Defra, 2012a). This growth in productivity will be limited to the areas where other facilitating factors exist, especially water supply (Rowland & Fleck, 2012). The changes in the climate will favour some species (including native species and commercially grown tree species) in some areas, while leading to deteriorating conditions for others. In the Grampian region where Tarland catchment is located the CCRA for Scotland (Rowland & Fleck, 2012) has assessed the likely changes in timber yields for the main tree species (Figure 7.11) based on Forest Research's Ecological Site Classification tool (Pyatt *et al*., 2001). The assessment showed an overall improvement of the productivity yield in the Grampian region for most tree types except for Silver birch, which presents a slight decrease of the yield into the future. The conditions will be more favourable for coniferous woodland compared to deciduous trees, with large differences between the expected yields. In the rest of UK, the expected positive shift in yield is considerably less or reversed to show a decreasing trend for coniferous trees (Defra, 2012a).

The CCRA for Scotland has argued that Sitka Spruce will benefit the most from climate change. Other studies however have linked Sitka Spruce with drought related diseases such as tree mortality and stem cracking in the east of Scotland (Green & Ray, 2009; Petr *et al*., 2014, Ray, 2008). Drought damage and root disease infections (e.g. *Armillaria* spp. and *H. annosum*) affecting Sitka spruce and other species are expected to worsen in eastern Scotland as a result of climate change (Green & Ray, 2009). Damage to Scots pine and larch species as a result of bluestain fungi and bark beetle infection could increase, particularly in areas associated with drought stress. Norway spruce will be affected by more extended and severe top dying particularly in the east. Mature deciduous woodland such as oak, ash and beech could also show a decline in health in drought prone areas. Matching the right tree to the right place will become critically important with climate change (Forestry Commission, 2010). Hence, species vulnerable to droughts such as Sitka Spruce, Norway spruce, Beech and Larch should only be planted in areas with sufficient soil moisture under the current climate whilst also considering the projected effects of climate change. Scots Pine and Douglas fir are more tolerant species to droughts, and could be better options for susceptible areas.

The increased waterlogging likely to result from climate changes could also make forests (especially non-native woodland) more ecologically vulnerable in the future. Diversification could be the answer in managing the risk of damage to forests: from broadening the choice of genetic material and mixing tree species in different ways, to varying management systems and the timing of operations (Ray, 2008; Ray *et al*., 2010).

The effectiveness of afforestation options decreases as the magnitude of extreme weather events increases. For large events (100 year return period events) the effectiveness of full afforestation with coniferous species decreased, achieving a reduction of 61% in the summer and 30% in the winter, for the peak flow of short intensity events (i.e. 7 hours). Model results showed a comparable decrease in the flow peaks for all levels of afforestation and woodland types up to the 2080s. The interception loss as a percentage of precipitation decreased for increased event magnitudes (Calder, 1998; Nisbet *et al*., 2011), reaching a maximum of 6-7 mm day^{-1}. The ability of woodland to reduce overland flow lies in its capacity to receive and store more water, and in increasing the hydraulic conductivity of the soil (Calder *et al*., 2003; Thomas & Nisbet, 2007). However this effect is limited by tree age, soil type and soil water holding capacity which decreases in the winter when most flooding events occur. Thus as the extreme weather event magnitudes increase with climate change, the effectiveness of afforestation options is expected to decrease.

The results show that even if increased levels of afforestation are achieved in the catchment (e.g. full afforestation with coniferous woodland), the peaks are still expected to increase for the future. Full afforestation with coniferous woodland may reduce the flood return period from the current 1 in 10 to a 1 in 5 flood event, though by the 2080s under the same afforestation option flood peaks equivalent to a 1 in 20 event could be generated as the rainfall events become more extreme. This suggests that the climate overrides the changes in land use and that while afforestation will play a role in decreasing the flood risk, the changes in climate will be the main factor shaping the hydrological behaviour of the catchment into the future.

This assessment considered that trees under different afforestation options are fully matured. Realistically, if the trees are planted today they will be the most effective after the 2050s, depending on the tree species. Coniferous woodland requires less time to reach a full potential for flood risk reduction, whilst deciduous woodland may not reach its maturity until the 2080s. This time delay needs to be considered when new woodland is used to reduce the flood risk.

As the human population increases, housing issues could be exacerbated, and more people could opt to live on floodplains. In Scotland 60% more residential properties could be at risk of flooding by the 2080s (Rowland & Fleck, 2012). Traditional measures for protection have been based on building defence walls, but as the risk increases under an uncertain climate, these existing structures will no longer be able to provide sufficient protection. The afforestation options provide greater flexibility compared to structural measures, and have adaptive capacity to deal with the uncertainty of climate change. However many challenges exist in implementing such measures, particularly as they involve changes in land use which are expected to decrease the food productivity potential.

Extensive afforestation could help to alleviate the increased flood risk that is posed by the changes in climate, but in catchments such as Tarland this is unlikely to happen. The land use scenarios provide plausible afforestation potentials under different socio-economic pressures. International and national legislation and targets will impact on the catchment, the land use scenarios offer a framework to explore futures directed by drivers that are outside of the control of the local decision makers. The land use scenarios integrate changes in land use that result from these interactions with climate for the 2050s projections. The assessment of climate change impacts cannot ignore concurrent change in socio-economics – the context of climate change – because these changes may amplify or reduce the impacts of climate change (Carter *et al*., 2001).

The results suggest that under the Local Stewardship and Global Sustainability scenarios a peak flow reduction of more than 5% could be achieved for 7 hour event durations and across different event magnitudes (except for 100 year rainfall return periods with winter antecedent conditions). Planting deciduous woodland is the expected outcome under these two scenarios, so a decrease of the high flows could be even higher, if the expansion was achieved using coniferous woodland instead of deciduous. Scots Pine is a native coniferous tree species, though with a slower growth compared to Sitka Spruce. It provides multiple benefits including landscape amenity associated with naturalness. Scots Pine could thrive in the Grampian region under future climates (Rowland & Fleck, 2012) and it is a more resistant species to drought making it a good option for Tarland.

World Markets and National Enterprise scenarios each suggest the same percentage of woodland under socio-economic pressures (4% coniferous). However there are differences in the results between each scenario which can be explained by variations in the location of new woodland. Thus, it can be concluded that the differences in flow generation between World Markets and National Enterprise is a result of location, whilst between World Markets and Global Sustainability it is the type of woodland chosen for afforestation.

Most coniferous woodland promoted in World Markets and National Enterprise scenarios is used for timber production. Typically coniferous woodland is harvested when it is 40 to 70 years old. While more environmental friendly methods are now considered, by which small blocks are clear-felled at a time, a decrease of effectiveness in reducing the high flows is nevertheless to be expected during harvesting cycles. Leaving the trees as permanent forest could be an option. By planting species that are efficient in supplying a wide range of ecosystem services (e.g. biodiversity, flood risk protection, carbon sequestration), long term benefits could be achieved.

Afforestation to different extents driven by different policy targets should not be seen solely from the flood alleviation perspective. The strength of the approach lies in their potential to increase the overall system resilience of the catchment in order to counteract the adverse impacts of climate change across a range of other ecosystem services as well as flood alleviation. EbA promotes the multi-benefit perspective and recognizes the importance of integrating an ecosystem services perspective to catchment management.

The benefits and disbenefits that afforestation options have on ecosystem services, considering the changes in climate, are assessed in the next chapter. The trade-offs and emerging conflicts are provided along with an overall discussion of their likely impacts.

7.6 Summary

This chapter has presented the results of the assessment of afforestation options and land use scenarios into the future. Afforestation options have been assessed for the 2020s, 2050s, and 2080s for extreme weather events based on the UKCP09 climate projections. Model simulations were carried out using the WaSiM-ETH hydrological model for different rainfall event durations and event magnitudes. The results suggest that afforestation options could play an important role in flood alleviation for future climates. Their effectiveness will be subject to the level of afforestation, tree type and event magnitude. The rate of the flow peak decrease, will increase with higher percentages of afforestation, but it will be significantly higher for coniferous woodland than for deciduous. However, as the climate changes, woodland expansion measures will be less effective at reducing the flood risk.

As previously discussed, the potential for woodland expansion depends on socio-economic factors, often outside of the control of the local stakeholders. The land use scenarios provide a framework to explore different plausible futures, under different international and national pressures and local targets. They have been developed by integrating the changes in climate by 2050 and consequent changes in land use. An increase in land classified as 'prime agricultural land' is projected for areas of Tarland by 2050, and this is likely to have an important role to play in contributing to food security targets in the catchment, thus making afforestation unlikely on land of agricultural potential (Brown & Castellazzi, 2014).

Changes in the hydrological response were noted between the land use change scenarios, though the differences are not large. The priorities assumed for World Markets and National Enterprise scenarios lead to the same percentage of afforestation (4%) of coniferous woodland, so the difference in their response is directly linked with the location of new woodland. Similarly, both Global Sustainability and Local Stewardship assume a 21% increase over the current woodland cover, however in this case it is deciduous woodland that is considered for afforestation. Thus the main difference between the land use scenarios with regard to flood risk reduction is explained by tree functional type (coniferous vs deciduous) and the location of the woodland (upland or lowland, which is mainly manifested through the land use which the woodland replaces).

Woodland expansion options have been assessed with a focus on flood alleviation, but their benefits could go well beyond this factor. The next chapter explores the ecosystem services that different options could provide, with a consideration for the trade-offs that need to be negotiated.

Chapter 8. Ecosystem based Adaptation approach for evaluating the afforestation options and land use scenarios

8.1 Introduction

Ecosystem based Adaptation provides a valuable perspective and approach for responding to the challenges of climate change that can complement traditional engineered options. EbA adaptation uses biodiversity and ecosystem services as an overarching framework guiding strategies to help create more resilient communities that have greater adaptive capacity to alleviate the negative impacts of climate change (Jones *et al.*, 2012). The key principle of EbA is to develop management responses that work in tandem with processes in the natural environment and thereby help in creating more resilient communities by buffering adverse impacts.

EbA approaches include sustainable agriculture, integrated water resource management and sustainable forest management interventions that seek to harness the resistance to change and recoverability (resilience) of environmental systems in responding to the negative impacts of anthropogenic climate change (Colls *et al.*, 2009; Holling, 1973; Imperial, 1999; Munang *et al.*, 2013). Whilst EbA strategies contribute in reducing the negative impacts of climate change, they provide a range of other benefits to local communities through the maintenance and enhancement of ecosystem services underpinning human well-being, either directly in the case of food security and flood protection, or indirectly through factors like biodiversity, carbon sequestration, and waste decomposition. Appropriately designed ecosystem management initiatives can contribute to climate change adaptation by promoting good ecosystem management practices and their integration into global, regional, national and local climate change strategies and action plans (Colls *et al.*, 2009).

The role of ecosystems in adaptation is recognized globally through the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD) and the United Nations Convention to Combat Desertification (UNCCD) (NEA, 2011). In Scotland the Land Use Strategy (The Scottish Government,

2011) sets the policy context by which ecosystem approach are included in decision making that affects land use.

The UKNEA has provided a summary analysis of the state of ecosystem services in the UK. In Scotland 43.7% of ecosystem services indicators were reported to be deteriorating or degrading and only 16.5% showed signs of improvement (NEA, 2011). This situation has mainly occurred due to an increase in provisioning services (notably food and fibre) at the expense of regulating services (e.g. for water quality, water flow and climate regulation), and these trends are expected to continue unless there are major changes in policy, land management and behaviours. In terms of habitats, woodland is indicated to show the greatest improvement in ecosystem service delivery, compared to the remaining key habitats in Scotland (cf. meta-analysis, see Appendix A), which highlights the importance of woodland for human wellbeing (Aspinall *et al.*, 2011).

Example projects that developed an integrated approach to ecosystem services in practice include the Land Use Pilot Project, the River Tweed Catchment Management Planning Initiative, the Stirling Ecosystems Approach Demonstration Project and Carse of Gowrie: Adapting to Climate Change (Davidson *et al.*, 2015; LUC & STAR, 2014; Tweed Forum, 2010). These projects included the assessment and mapping of ecosystem services and stakeholder engagement using maps. The case study area for the present study (Tarland Burn catchment) is part of the wider Aberdeenshire Land Use Strategy Project (Davidson *et al.*, 2015). The project is due to be completed in April 2015 and it is aiming to map natural assets and create outputs that can be used for strategic land use planning and decision making.

Due to the spatial heterogeneity of ecosystem services, mapping their distribution can provide complex information (Burkhard *et al.*, 2012). Interest in the valuation and mapping of ecosystem service has increased exponentially since Costanza *et al.* (1997) published a first global assessment of ecosystem services. Several tools, methods and approaches have since been developed to support ecosystem service assessment. Some methods use primary data to map ecosystem services (i.e. sampling of empirical data on supply and demand for services) whilst others rely on secondary data (i.e. land cover proxy based methods). Most studies rely on land use/cover data as a proxy for ecosystem services supply using look-up tables to attribute scores for ecosystem services to particular land cover types, an approach made necessary because of the current restrictions on availability of primary data for many ecosystem services.

The spatial correlation among different services varies widely and spatial patterns of land cover can be linked with measures of human activity (Riitters *et al.*, 2000). Although there is a rich literature on the economic valuation of the environment, research on how values vary spatially has only recently begun to emerge (Naidoo *et al.*, 2008).

The ecosystem services are divided between regulating, provisioning, cultural and supporting and some ecosystem services are easier to map than others (Naidoo *et al*. 2008). As a result the mapping of ecosystem services tends to be biased towards those services where data are more readily available. This is reflected in the current literature, as discussed in the review by Crossman *et al*. (2013) which highlights a focus of existing mapping on regulating and provisioning services. This is unsurprising as this type of ecosystem services is relatively easier to quantify and the data required are more readily available from existing environmental monitoring strategies. The most mapped ecosystem services are climate regulation, food provision, water supply and the regulation of water flows and tourism and recreation (Crossman *et al.*, 2013). However because of the different level of information available for contrasting services, there is a danger of having a misrepresentative image of the overall state of ecosystem services.

There is a move towards more sophisticated methodologies that use ecosystem services models and value functions which integrate a number of spatial variables, and can be validated using primary data (Schägner *et al.*, 2013). Complex tools such as InVEST (Kareiva *et al.*, 2011; Tallis *et al.*, 2013), ARIES (Bagstad *et al.*, 2011; Villa *et al.*, 2011), SENCE (Environment Systems, 2014), LUCI (Jackson *et al.*, 2013) and EcoSERV-GIS (Feng *et al.*, 2011) have been developed and are now being tested using a range of secondary datasets. They provide a more comprehensive understanding of the current state of ecosystem services, but their use is limited by the availability of the data required, and the need for additional time and human resources.

In this chapter, land use change options have been evaluated from an ecosystem service perspective to understand the impacts that the NFM options could have on their delivery. The potential for delivering ecosystem services has been calculated by linking it to the different habitat classes in the catchment. The approach selected for this assessment is based on an evaluation of the relative change in the potential for delivering ecosystem services, and the methodology has previously been successfully applied (Brown & Castellazzi, 2014; Fürst *et al.*, 2010). Maps have been developed to explore spatial issues in relation to the delivery of ecosystem services using land cover as a proxy in the potential for service supply. In terms of land use change options, a comparison between woodland expansion and improving the efficacy of the existing drainage system has been performed to explore the importance of incorporating ecosystem service weighting in NFM option implementation as an indicator for the wider co-benefits.

8.2 Methodology

The methodology for the assessment of ecosystem services is based on the UK National Ecosystem Assessment (NEA, 2011). Afforestation options were evaluated through a semi-quantitative analysis of the relative change in the potential for delivering ecosystem services. Scores in the range of 0 to 3 (Table 8.1) were assigned for each habitat class, with 0 being a low potential and 3 being a high potential for delivering ecosystem services.

Table 8.1 Scoring system

Potential for delivering an ecosystem service	Score
Low	0
Medium low	1
Medium high	2
High	3

This scoring method has been previously employed successfully (Brown & Castellazzi, 2014; Fürst *et al*., 2010). Other studies (Haines-Young *et al*., 2006; Willemen *et al*., 2008) have attempted to include the spatial variability of some functions. However, there can be a bias towards the ecosystem services for which data are more readily available (Crossman *et al*., 2013).

The ecosystem services important in forest systems relevant for the catchment, and previously identified by the UK NEA (2011) are: food production, fibre and timber, water supply, carbon sequestration, flood protection, disease and pests reduction, water quality, air quality, soil quality, biodiversity and with business income as an added benefit. Some services were not mapped due to the weak evidence linking habitats to certain services. Here, carbon storage includes both soil and vegetation carbon sinks. Business income refers to income from farms, arable land, timber and fibre, and game; this is more properly distinguished as an economic benefit of the land rather than a service but is included because of its importance to local people. Table 8.2 presents the indices for each habitat class based on LCM07 linked with its potential to deliver certain ecosystem services.

Table 8.2. Scores for each habitat class based on their potential to deliver ecosystem services

	Food productivity	Business income	Fibre/timber	Carbon storage	Soil quality	Water quality	Flood regulation	Biodiversity	Recreation
Semi-natural	0	1	1	3	2	2	2	2	3
Arable intensive	3	3	0	0	0	0	0	0	1
Deciduous woodland	1	1	2	2	2	2	2	3	2
Coniferous woodland	0	2	3	2	1	1	3	1	1
Wetland and water	1	1	0	2	2	3	3	**3**	2
Improved grassland	2	3	1	1	1	0	1	1	1
Built up gardens	1	2	1	1	2	2	1	1	2

The indices were adapted from Brown & Castellazzi (2014) and modified for some ecosystem services to suit the current level of understanding of their role as presented in earlier chapters (e.g. coniferous woodland has a higher potential to deliver flood protection compared to deciduous woodland). They have been developed using expert based summary assessments on land use and broad habitats in UK (NEA, 2011).

Based on model simulation results the flood alleviation potential of non-native (coniferous) woodland and native (deciduous) woodland has been adjusted. A score of 3 was assigned for coniferous and a score of 2 for deciduous from an initial score of 2 for both land use classes. This part of the analysis shows the advantages of detailed modelling for improving an initial qualitative assessment of relative change, as it provides better evidence on which to justify the relative differences between land cover types. Similarly, the indices for soil quality was changed to 1 for coniferous woodland due to acidification issues (Nisbet *et al.*, 2011) that occur generally in non-native woodland, and which are exacerbated during clear-felling of commercial forests. For timber production, broadleaved woodland has been assigned a score of 2 (initially 1) as there is a large tradition of deciduous commercial woodland such as for beech and sycamore species (Forestry Commission, 2003).

The indices were linked with the percentage of the different habitat classes in each grid cell (50 m resolution) for different land use change options, to calculate the areal capacity for delivering ecosystem services. The capacity, a product of area and land use class, was then normalized as a percentage value for each ecosystem service, with the maximum value providing a standardized value against which the relative changes of capacities from other scenarios could be evaluated.

Opportunity maps have been developed using the indices in Table 8.2, and these allow for the spatial representation of the potential of different habitat classes to deliver ecosystem services. This approach has been tested in mapping ecosystem services in England (Dales *et al*., 2014) and to assess the flood risk alleviation potential in Bulgaria (Nedkov & Burkhard, 2012). In creating the individual ecosystem service maps, habitat scores have been attributed to each 50 m grid cell and the results were displayed using an appropriate colour shade.

The method used for mapping the ecosystem services in this chapter has the advantage of requiring limited amounts of data, it is simple to use and provides maps of those habitats that are important in the provision of ecosystem services. The land cover map used for the assessment does not include details about the condition of the habitat, and so the baseline condition of the ecosystem service could not be assumed, hence the emphasis on relative change. Whilst the method does not include the impact of spatial distribution on the delivery of ecosystem services explicitly, and it does not consider the flows and demands for ecosystem services, it is an easy and useful visualization tool for decision makers, and so it can aid landscape sustainability assessments.

The land use scenario based on socio-economic drivers have previously been evaluated from an ecosystem service perspective in Brown & Castellazzi (2014). The scoring system was adjusted and a discussion is provided in this chapter. The land use scenarios have been detailed in the methodology section of Chapter 6.

8.3 Ecosystem services appraisal of land use scenarios and afforestation options

Changes in land cover have an impact on the capacity of ecosystems to provide goods and services (Burkhard *et al*., 2012). The changes in the delivery of ecosystem services under different land use options and land use scenarios are driven by the increased level of afforestation which will enhance the delivery of woodland related ecosystem services, whilst decreasing the delivery of other ecosystem services associated with the replaced habitats.

Table 8.3 summarizes the total woodland percentage for land use options assessed in Chapter 6 including the variation in the woodland type (i.e. coniferous and deciduous woodland).

Table 8.3. Woodland expansion percentage for the afforestation options and land use scenarios

	% woodland	% woodland increase	New woodland	Total coniferous (%)	Total deciduous (%)
Afforestation layouts					
50% coniferous	50	24	Coniferous	45	5
50% deciduous	50	24	Deciduous	21	29
75% coniferous	75	49	Coniferous	70	5
75% deciduous	75	49	Deciduous	21	54
Full afforestation coniferous	99	74	Coniferous	94	5
Full afforestation deciduous	99	74	Deciduous	21	78
Socio-economic scenarios					
World Markets	30	4	Coniferous	25	5
National Enterprise	30	4	Coniferous	25	5
Local Stewardship	47	11	Deciduous	21	16
Global Sustainability	47	11	Deciduous	21	16
Drainage					
Improved drainage (5 dis*)	26	0	-	21	5

* 5 dis refers to 5 m spacing drainage density

8.3.1 Ecosystem services appraisal of afforestation options

8.3.1.1 Ecosystem services for Tarland

Afforestation options are derived by replacing existing land cover with coniferous or deciduous woodland. The alterations in the land cover are an indication of how the potential for delivering ecosystem services will change, as different ecosystems have different capacities to deliver ecosystem services (Nedkov & Burkhard, 2012).

Table 8.4 presents the habitat classes that compose each afforestation option and variations (Standard Deviation) for each spatial layout over the 5 simulations used for the project.

Table 8.4. Percentage land covers for each afforestation option

	Current land use	Mean 50% D.	SD	Mean 50% C.	SD	Mean 75% D.	SD	Mean 75% C.	SD
Semi-natural	15.07	17.18	0.35	17.18	0.35	7.96	0.27	7.96	0.27
Arable intensive	17.21	13.03	0.24	13.03	0.24	7.64	0.13	7.64	0.13
Native woodland	4.74	28.61	0.02	4.74		53.58	0.01	4.74	
Non-native	21.42	21.42		45.29	0.02	21.42		70.26	0.01
Wetlands	0.32	0.32		0.32		0.32		0.32	
Improved grassland	29.45	19.17	0.35	19.17	0.35	8.81	0.38	8.81	0.38
Built up gardens	1.03	1.03		1.03		1.03		1.03	

*D-deciduous, C-coniferous, SD-Standard Deviation

The capacity of each afforestation option to deliver ecosystem services, compared against the current land use, is presented in Figure 8.1. The assessment shows large differences across different levels of afforestation and between the coniferous and deciduous woodland.

Coniferous woodland has important benefits for flood regulation, fibre and timber, and business income. Coniferous woodland was shown in earlier chapters to have the potential to significantly reduce the flood risk, subject to the trees species and percentage of afforestation. It has the potential to moderate rainfall events and stream hydrographs, delaying and reducing flood events (Nisbet *et al.*, 2011). Forests plantations also provide raw timber for commercial and domestic use for wood boards and paper pulp and offer an alternative for traditional building materials (e.g. concrete, steel) (Suttie *et al.*, 2009).

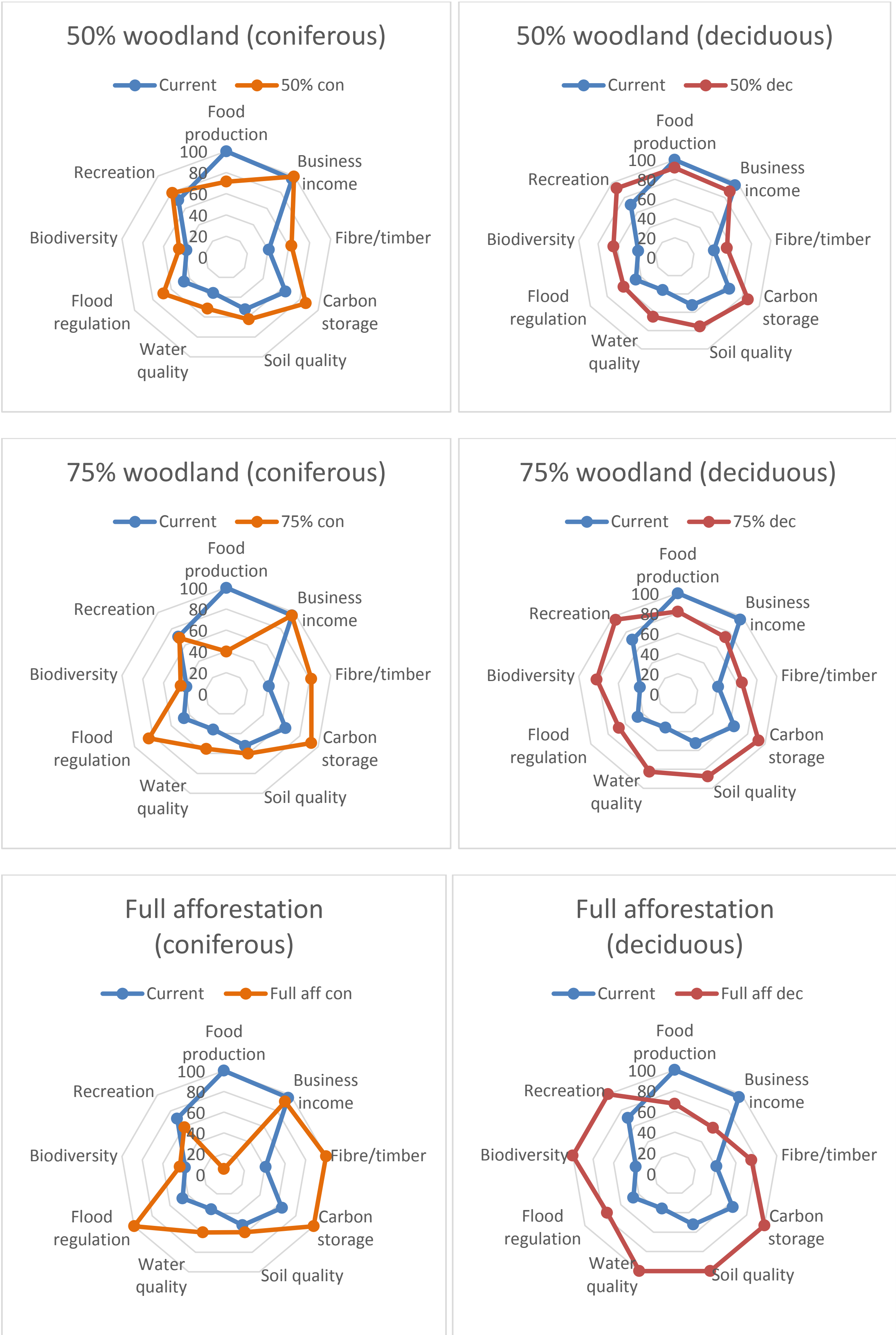

Figure 8.1. Potential for delivery of ecosystem services for Tarland Burn catchment across different afforestation options

Afforestation with coniferous plantations will be less beneficial for biodiversity, recreation, soil quality and water quality. Coniferous woodland planted as a crop tends to have lower biodiversity interest than broadleaf woodland (Humphrey *et al.*, 2003). This is partly because coniferous commercial woodland is predominantly composed of introduced species, in combination with the close planting of a monoculture. Moreover, management practices to reduce pests and competition from other species can also reduce biodiversity. Coniferous woodland can be used for recreational purposes, but as this type of woodland is predominantly planted for timber it is usually less amenable to this service due to its structure and simplified vegetation structure.

Tree roots decrease erosion rates by holding soil in its place and preventing it from getting blown away by the wind. However, harvesting and felling operations associated with coniferous planting can disturb the soil, and have the potential to increase water turbidity, sedimentation and acidification leading to potential water and soil quality issues (Nisbet *et al.*, 2011). There is also less organic matter under coniferous woodland compared to deciduous woodland (Terumasa & Yoshito, 2004).

The lowest score recorded for food production was for the full afforestation with coniferous woodland. Commercial woodland provides little scope for food production other than grazing in wood-pasture systems. Native woodland provides greater benefits for food provision including game, berries, honey, fungi and medicinal plants (Emery *et al.*, 2006; Martin *et al.*, 2006).

Deciduous woodland scored highly on a large number of ecosystem services delivering benefits for water quality, soil quality, biodiversity, recreation and carbon storage. Woodland has been linked to decreased erosion rates which have a positive impact on water quality by reducing suspended sediments and transport to the stream. Moreover woodland can reduce pathways between a source and receptor, and so stabilize contaminated land (Moffat *et al.*, 2010). Furthermore, broadleaved woodland provides a critical habitat for the development of a healthy ecosystem delivering benefits for biodiversity (Hopkins & Kirby, 2007; Humphrey *et al.*, 2003; Kirby *et al.*, 2005). If deciduous woodland is planted as native forest it will often be managed as nature reserves with footpaths, providing a valuable recreation and tourism resource (Forestry Commission England, 2010). However if it is created as a plantation, its benefits for recreation will be reduced. The benefits for these services is directly linked with the level of afforestation, thus the greater the expansion with deciduous woodland, the greater the benefits.

By contrast, high levels of deciduous woodland are linked with lower levels of food production compared to the current land uses that are mainly agricultural, and much lower for conversion of intensive arable land to woodland. Afforestation with native woodland has lower potential for flood alleviation, fibre and timber and business income, compared to coniferous woodland. Modelling results show that deciduous woodland has a relatively small benefit for flood alleviation. This is mainly due to lower water use and interception loses particularly in the winter when most floods occur (Calder *et al.*, 2003), although the modelling did not include hydraulic effects through increased surface roughness.

Both types of woodland scored highly on carbon storage potential though coniferous woodland may sequester more carbon than deciduous as it has a faster growth rate. A study at Kielder Forest (Greig, 2008) approximated that on average each tree is locking up to 0.55 kg of carbon per year, equivalent to 2 kg of carbon dioxide. The exact amount will depend on tree species, age and tree management. Young trees absorb more carbon dioxide because of their rapid relative growth (Broadmeadow & Ray, 2005) but as trees age, the rate reaches an equilibrium between the amount of carbon absorbed and the amount lost through respiration and tree decay. Moreover forests lock carbon in their soils, with up to four times more carbon stored than in the trees. Thus, maintaining forested areas will ensure these carbon stocks are preserved. Soil aeration as a result of tree planting, and felling and drainage, could release carbon especially on organic-rich soils. Moreover trees planted on deep organic rich and peat soils increase mineralisation rates resulting in a negative impact on carbon storage (Cannell, 1999). In the Tarland catchment the peaty soils are no deeper than 0.50 m (the threshold for definition of deep peat), so it is unlikely to be a restricting factor for planting trees.

8.3.1.2 Opportunity maps

Opportunity maps were developed using existing land cover data as a proxy for ecosystem service provision, to identify the areas of the catchment with the highest potential for delivering ecosystem services. Figure 8.2 illustrates the potential of all ecosystem services applied over the current land use. The maps for each ecosystem service for all woodland expansion options are presented in Appendix D.

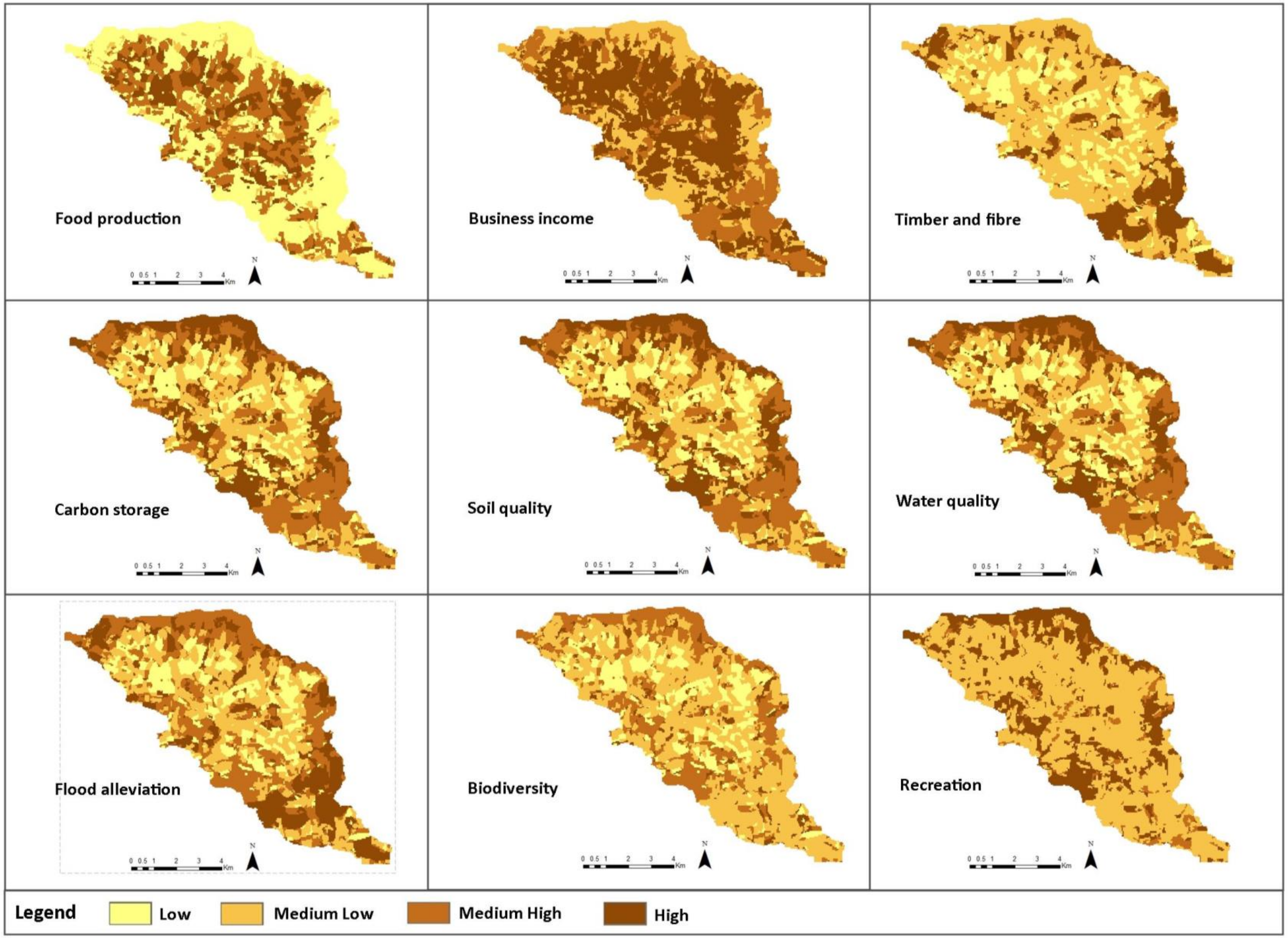

Figure 8.2. Map with potential for delivering ecosystem services for the current land use

From the maps (Figure 8.2 and Appendix D) it is possible to observe that while new habitat classes have a high capacity to deliver some services, it will come at a trade-off for other services. The upper areas in Tarland have a high potential for carbon storage, water and soil quality and recreation. The valley bottom is providing important benefits for food production and business income from agricultural land. Overall the middle area of the catchment, between the river valley and the upper hills has the highest potential to deliver benefits for ecosystem services. This conforms to the idea of a ‘squeezed middle’, as it has been recognised at a national level (Slee & Pinto-Correia, 2015) and which also occurs locally in many of the agricultural catchments where there are competing demands to meet different targets on this land of intermediate quality.

The overall potential for delivering ecosystem services was calculated for all afforestation options by adding the percentages of different land covers with their potential for each ecosystem service. The values were then indexed to 100 and the results are presented in Figure 8.3.

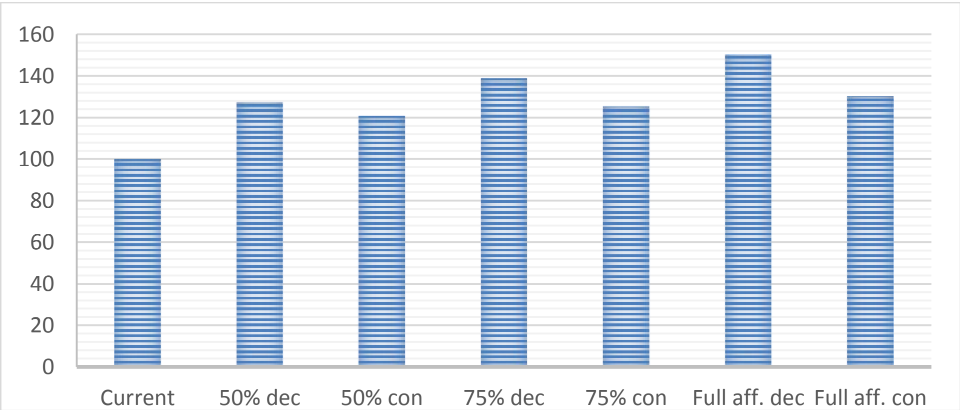

Figure 8.3. Overall potential for delivering ecosystem services (indexed to 100)

If an equal weighting is considered for all ecosystem services, an overall enhancement of the potential for delivering ecosystem services can be seen for all percentages of woodland increase. The potential increases with an increased afforestation percentage, and it is higher for deciduous woodland compared to coniferous woodland. However full afforestation would limit the accessibility of people to live in the catchment, thus referencing to the anthropogenic notion that benefits are only useful when there are humans to benefit from them (Fisher *et al.*, 2009).

8.3.2 Ecosystem services appraisal of land use scenarios

The use of land use scenarios to investigate change in the delivery of ecosystem services has been previously applied. Swetnam *et al*. (2011) used InVEST to map carbon storage potential in Tanzania. The appraisal of land use scenarios from an ecosystem service perspective in Tarland has been performed by Brown & Castellazzi (2014). The scoring system has been modified to reflect the current level of understanding of how different land cover types contribute to delivering certain ecosystem services as already discussed in the methodology section. The results are presented in Figure 8.4 and a discussion of the overall impacts is provided below.

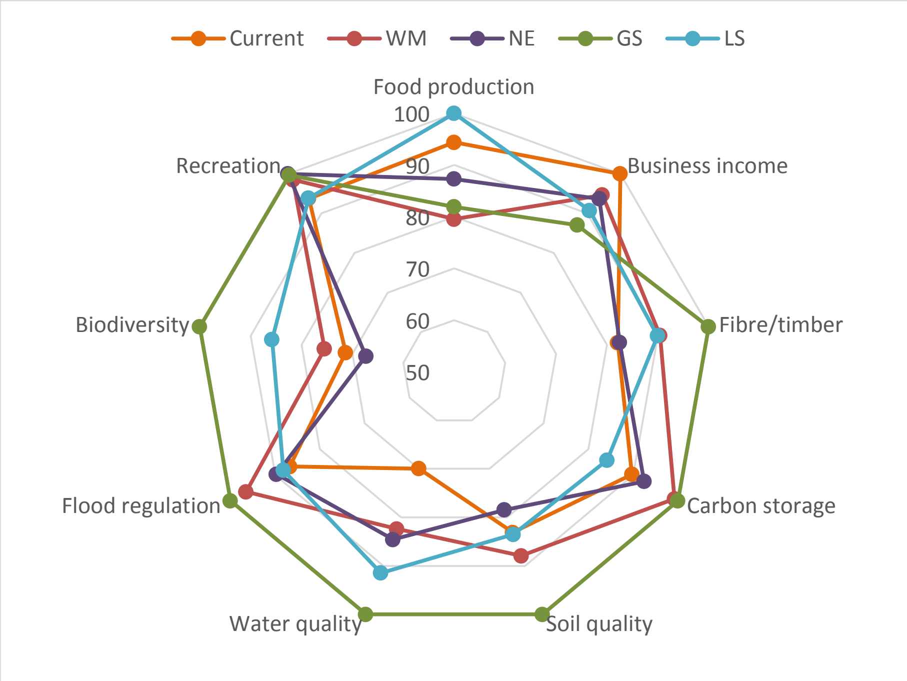

Figure 8.4. Ecosystem services appraisal of land use scenarios

The National Enterprise scenarios enhance the business income function and food production, whilst decreasing soil quality and biodiversity, which is mainly a result of the conversion to intensive arable land. The World Markets scenario leads to a small decrease in the delivery of food production as less land is used for agriculture and increases of business income and flood regulation, which can reflect the changes to coniferous plantation from other land use types. Under the Global Sustainability scenario, the highest number of ecosystem services could be achieved, but this could also potentially decrease the food production and timber and fibre ecosystem service types. The Local Stewardship scenario is noted for the enhancement of food production, water quality and soil quality and biodiversity, as a result of an emphasis on low

Table 8.5. Impact of woodland expansion and drainage restoration options on ecosystem services

Service group	Ecosystem services	Woodland expansion	Restoration of existing drain network performance
Provisioning	Crop	↘	↗
	Livestock	↘	↗
	Fish	→	↘
	Trees/stand vegetation	↑	→
	Water supply	↘	↘
Regulating	Climate regulation	↗	→
	Carbon sequestration	↑	→
	Flood	↗	↗
	Disease and pest control	↗	→
	Fire risk	↓	→
	Water quality	↘ ↗	↘ ↗
	Soil quality	↗	↘
	Biodiversity	↗	→
Cultural	Sense of place	↘	→
	History/religion	↘	→
Supporting	Soil formation	↗	→
	Nutrient cycling	↗	→
	Water cycling	↗	→
	Oxygen production	↗	→

Legend

↑	Significant positive impact	↓	Significant adverse impact	→	No impact
↗	Less significant improvement	↘	Less significant adverse impact	↘ ↗	Mixed impact

intensity agriculture and deciduous woodland. The business income factor would decrease, but the land is valued more for the delivery of community and cultural benefits that are incompletely quantified in this assessment.

8.3.3 Woodland expansion and drainage

Two NFM options have been assessed for the current climate in Chapter 6 – woodland expansion and improved efficacy of existing drainage. To understand the impacts these NFM measures have on ecosystem services, and allow the comparison between them, they were assessed using the methodology from the meta-analysis section (Appendix A). This framework is based on the UK NEA (2011), and distinguishes between provisioning, regulating, cultural and supporting services. The results are presented in Table 8.5.

If an equal weighting is considered for all ecosystem services, then overall afforestation options could provide greater benefits for a wide range of ecosystem services, compared to drainage though both measures are potentially bad for water quality. Woodland expansion, particularly with coniferous trees, could decrease the low flows thus impacting on aquatic ecology (Nisbet *et al.*, 2011), whilst drainage has been associated with water quality issues (i.e. increased organic carbon, water discoloration) across a series of studies (Chapman et al., 1999; Moore, 1987; Wallage *et al.*, 2006). However, improved drainage could sustain higher flows in the summer beneficial for aquatic ecosystems (Krause *et al*., 2007). Afforestation options will take a long time to achieve their full potential in reducing the flood risk, so other measures might be necessary to achieve more immediate results. Improving the efficacy of drainage systems is beneficial for food production (crops and livestock) but it provides little benefit for other services. The modelling results show that drainage attenuates the flood risk in Tarland, however this could not be generalized. Studies undertaken in the UK noted mixed catchment responses as a result of drainage implementation (Blanc *et al*., 2012). If food provision receives a higher weighting e.g. food production is three times more important than any other service, than drainage could be a better option for multiple service delivery. Ultimately which option is the best in terms of achieving multiple ecosystem services will depend critically on the weighting that is considered for different services. In reality, the weighting is applied by different policy strategies that are involved in prioritizing targets for Scotland.

8.3 Discussion

Water quality and flooding issues are ongoing problems in the Tarland catchment, which makes the associated ecosystem services (water quality regulation and flood regulation) a priority in the river basin. Tarland catchment failed to meet the WFD 'good quality' status due to diffuse pollution and morphological alteration (The Macaulay Institute for Soil Research, 2009). Moreover, significant flooding issues have been recorded frequently both at Tarland and Aboyne, as documented in the Aberdeenshire Council Biennial Reports (Aberdeenshire Council, 1997, 1999, 2001, 2003, 2005, 2007, 2009). The delivery of the water quality ecosystem service would be higher for afforestation with deciduous woodland, but plantations with coniferous woodland have a significantly higher potential for delivering flood regulation ecosystem services. Modelling results are showing that increasing the woodland cover to 50% (from the current 26% mixed woodland) could decrease the Q_5 by 19%. However it will also decrease the Q_{95} (by 25%) potentially exacerbating water quality issues particularly in the summer when the water levels are low.

'The right tree in the right place' is promoted by Scottish Government policies through targeted woodland planting in areas where multiple benefits can be achieved (Forestry Commission, 2009). The linkage between woodland expansion and improvement for water quality is under represented, with limited Rural Priority options within the Scottish Rural Development Programmes that address (i) soil and water quality issues and (ii) the benefits for woodland expansion (Nisbet *et al*., 2011). Successful examples of afforestation for achieving water quality targets have been noted in Denmark, France and the USA (Nisbet *et al*., 2011). However, a number of design and management factors have been linked with diffuse pollution from forestry, and these need to be considered particularly for coniferous afforestation. High tree density near a stream (i.e. where no direct sunlight reaches the site) can reduce the water temperature, thus reducing the stream productivity, a decrease in the bank vegetation can facilitate erosion, with channel build up and greater gravel siltation (Broadmeadow & Nisbet, 2004). Inappropriate site selection for afforestation, which includes planting on acid-sensitive sites (Stevens *et al*., 1994) can also exacerbate water quality issues. In acid-sensitive parts of the UK, forestry has been linked to increased acidification of surface waters particularly during forest establishment, harvesting and road building (Nisbet *et al*., 2011). Finally, the aerial application of fertilisers and herbicides to new or young coniferous plantations on nutrient poor soils presents a significant risk especially within those catchment where the water quality is already an issue (Swift, 1990).

Tarland Burn catchment is very important for biodiversity as it is part of the wider River Dee Special Area of Conservation identified as part of Natura 2000 and the European Habitats Directive. The catchment is internationally recognized for its salmon, otter and freshwater pearl mussels. Afforestation using deciduous woodland could deliver greater benefits to the catchment for biodiversity. However, when considering timber and fibre, coniferous woodland yields the higher benefits. With the Scottish Government woodland expansion targets, catchments such as Tarland, where there is a high potential for afforestation, could become even more important for the delivery of timber in the future.

Carbon sequestration is prioritised by the Climate Change (Scotland) Act, which sets out the actions for Scotland to reduce its greenhouse gas emissions by 42% by 2020 and by 80% by 2050 from the 1990 levels. Woodland expansion is contributing to delivering this target. However changing the land use to woodland would impair the catchment's capacity to contribute to food security targets. Tarland is an intensive agricultural catchment, with 15.7% arable land and 39.4% improved and unimproved grassland. With more than 80% of the land in Scotland deemed as a Less Favourable Area according to EU Common Agricultural Policy criteria, woodland expansion may not be prioritised in areas with high agriculture yield.

Intensive agriculture has the lowest potential to provide multiple ecosystem services if an equal weighting of services is considered. Moreover, the performance could be limited by dis-services which reduce the productivity or increase production costs (e.g. competition for nutrients from undesired species). The delivery of ecosystem services will depend on how agro-ecosystems are being managed and designed (Zhang *et al*., 2007). Biodiversity could be enhanced by increasing the diversity of the vegetation, in order to maintain ecosystem services over a wide range of stress and disturbances (Swift *et al*., 2004). With an increased knowledge of how biogeochemical cycles and ecological interactions function, it is easier to shape ecosystem process in subtler and more beneficial ways (e.g. changing heavy fertilizers to soil nitrogen fixation through crop rotations when needed) (Swinton *et al*., 2007).

The idea of win-win approaches, suggests that multiple services can be delivered with no real trade-off against existing priority services (e.g. food production). This seems ethical in acknowledging the need to protect earth's systems, and highly marketable as it aims for no net loss to ecosystem services (McShane *et al*., 2011). However, in reality, a trade-off between the delivery of different ecosystem services is inevitably required. Some services appear together on the landscape while others appear to oppose one another (Bennett *et al*., 2009). Most services are not necessarily good surrogates for their alternative service types, and one cannot manage one service and expect to necessarily benefit other services also (Egoh *et al*., 2008). An example is enhanced carbon sequestration as a result of afforestation, with decreasing water availability as the evapotranspiration rates increase (Engel *et al*., 2005). The landscape provides simultaneous multiple ecosystem services which interrelate in complex and dynamic ways (Bennett *et al*., 2009). Efforts to engineer ecosystems can lead to the undesirable decline in existing ecosystem services. Globally, a focus on food and timber has led to a decline in flood control and biodiversity.

Dealing with trade-offs necessitates making some hard decisions, understanding that any choice will lead to some kind of loss, which for those directly affected might be a significant one. Frequently the trade-offs within choices are implicit without the full realization that something is potentially lost (McShane *et al*., 2011). Understanding the relationship among different ecosystem services is important, as this would help inform the potentially hard decisions that are required (Bennett *et al*., 2009).

In Scotland the delivery of different ecosystem services is pushed forward by complementary national, European and global policies, strategies and principles shaping the future of ecosystems. For example, through payment and incentive schemes farmers are encouraged to plant different crops, depending on the priorities of the Scottish Rural Development Program. Table 8.6 provides an overview of the national and European polices and the main ecosystem services that they target. The Land Use Strategy 2011 and National Planning Framework for Scotland 2004 apply to all ecosystem services as they promote integrated approaches to land management and land management decision making. At a European level, the European Commission has pushed forward key strategies e.g. the EU Floods Directive, the Water Framework Directive and Habitats Directive that have been embedded into the legislation of the member countries.

Table 8.6. National and European guiding strategies and actions in Scotland

<table>
<tr><th>Ecosystem service</th><th colspan="2">National policy</th><th>European Policy</th></tr>
<tr><td>Food productivity</td><td rowspan="9">Land Use Strategy 2011 & National Planning Framework for Scotland 2004</td><td>Common Agriculture Policy reform, 2013</td><td>EU policy framework to assist developing countries in addressing food security challenges, 2010</td></tr>
<tr><td>Business income</td><td>Scotland Rural Development Programme for 2007-2013</td><td>The Europe 2020 Strategy targets, 2009</td></tr>
<tr><td>Fibre/timber</td><td>Scottish Forestry Strategy, 2006</td><td>EU Forestry Strategy, 1998
EU Forest Action Plan, 2006</td></tr>
<tr><td>Carbon storage</td><td>Climate Change (Scotland) Act, 2009</td><td>EU CCS Directive on Geological Storage of Carbon Dioxide, 2009
EU Emissions Trading System (ETS) cap, 2013</td></tr>
<tr><td>Soil quality</td><td>The Scottish Soil Framework, 2009</td><td>Framework Directive for the Protection of European Soil, 2006</td></tr>
<tr><td>Water quality</td><td>The Water Environment and Water Services (Scotland) Act, 2003</td><td>Water Framework Directive, 2000</td></tr>
<tr><td>Flood regulation</td><td>Flood Risk Management (Scotland) Act, 2009</td><td>The EU Floods Directive, 2007</td></tr>
<tr><td>Biodiversity</td><td>2020 Challenge for Scotland's Biodiversity, 2013</td><td>EU biodiversity strategy to 2020, Habitats Directive, Birds Directive, 1992, Natura 2000</td></tr>
<tr><td>Recreation</td><td>Scottish Historic Environment Policy, 2011</td><td>European Landscape Convention, 2004</td></tr>
</table>

In reality these policies apply to a wide range of ecosystem services, as they aim for multiple benefits as seen in Figure 8.5. Strategies such as Scottish Forestry Strategy, Scotland Rural Development Programme, Land Use Strategy and National Planning Framework for Scotland aim to guide practices for a wide range of ecosystem services. Others e.g. Common Agriculture Reform, Scottish Soil Framework, Climate Change (Scotland) Act, Scottish Historic Environment Policy regulate a limited number of services. Interestingly, the delivery of flood risk protection is only required by the Flood Risk Management (Scotland) Act and partly by Water Environment and Water Services (Scotland) Act, although NFM options are clearly linked with other policies (e.g. Scottish Forestry Strategy, Land Use Strategy, and Water Framework Directive).

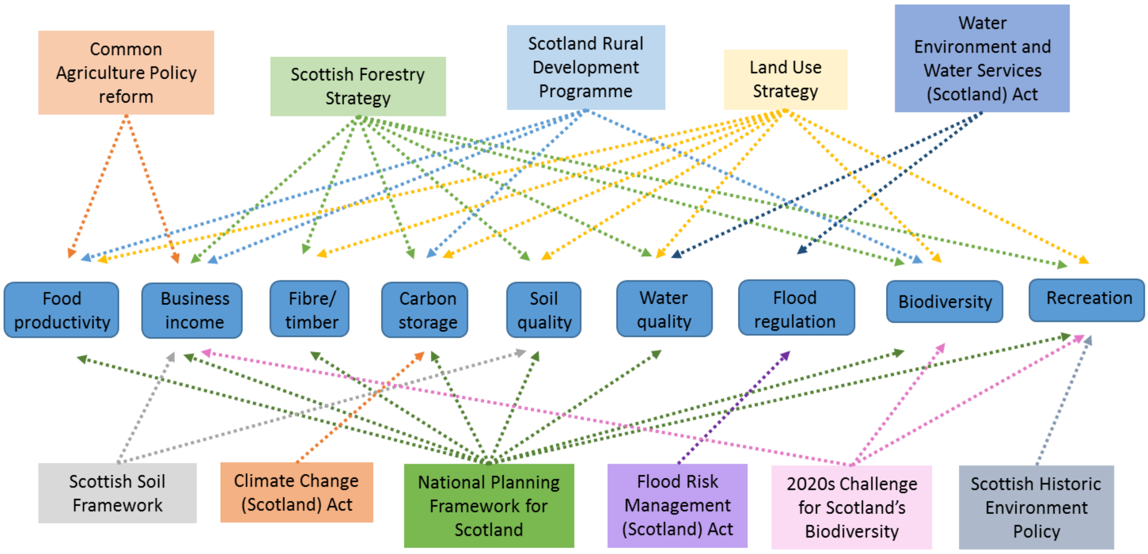

Figure 8.5. National policy targets for delivering ecosystem services

Conflicts of interest can occur between concurrent strategies when translated into plans and regulations at local scales. For example there is a potential conflict between the Strategic Plan for the National Forest state and the Forest Grant Schemes, and the provision of the Pollination (wild species and crops) ecosystem services (Muñoz-Rojas *et al.*, 2015). However, if national and local policies demand the continuous delivery of a wide range of ecosystem services from forest systems, including biodiversity, carbon storage and timber production, there is a high chance that it will fail to deliver some other services unless integrated climate adaptation measures are implemented (Ray *et al.*, 2014). Diversification could be the answer, with more varied species managed for low impact woodland systems (Ray *et al.*, 2008). Planting trees to promote mixed age cohorts and different tree species to broaden the genetic resource, as well as varying management systems and the timing of operations, is an essential basis for climate change planning and management.

The delivery of multiple ecosystem services is key to the EbA framework, but not all ecosystem services will be equally important in every catchment. This will depend on the existing issues in the river basin, societal pressures and policy targets. Fisher *et al.* (2009) noted that without human beneficiaries, ecosystem functions and processes are not translated into services. In other words, there must be a certain demand by people to define a particular ecosystem service although functions and processes will continue to provide a fundamental role in maintaining the overall earth system. However, the demands may change in the future, and whilst some potential ecosystem services might now have no beneficiaries, they could become critical for human-wellbeing under a combination of climate change and socioeconomic pressures (e.g. overpopulation). Knowing where there is a demand (actual and potential) for certain ecosystem services is very important for forward-looking environmental decision making, because it can indicate where interventions should be targeted by delineating high priority areas for protection and guiding the management of these services across different scales (García-Nieto *et al.*, 2013). However the position of supply and demand is often spatially disjunct (K. J. Bagstad *et al.*, 2013).

Conventionally, ecosystem services have been valued through market based approaches (Farley & Costanza, 2010). Over the past forty years, the rapid evolution of environmental valuation methods has favoured a more adaptive transdisciplinary approach that has contributed an important set of new tools, to estimate the value to society of ecosystem services (Swinton *et al.*, 2007). Understanding how ecological functions generate ecosystem services is fundamental to management, but equally important is understanding how humans perceive and value those ecosystem services. Recently ''payments for ecosystem services'' (PES) has emerged as a policy solution for regulating the economic and societal benefits in environmental decision making (Jack *et al.*, 2008). PES relies on incentives, and by altering private incentives to induce desired outcomes, PES schemes offer a direct, and possibly more equitable method for achieving environmental outcomes than other approaches. However, previous experience with incentive-based methods seem to suggest that it is very difficult to achieve simultaneous improvements to human well-being and ecosystem services whilst at the same time reducing costs (Jack *et al.*, 2008). Other concerns about the PES approaches have been raised (Redford & Adams, 2009), to suggest that economic arguments may outweigh noneconomic justifications for conservation services, and that there is a danger of maximizing single service systems to meet policy demands. Specifically, in vulnerable communities, PES schemes should prioritize the delivery of essential and irreplaceable ecosystem services, especially those that satisfy basic needs (Farley & Costanza, 2010).

Climate change will transform the landscape, forcing policy makers to re-think the way the land is being managed. In agriculturally intensive catchments like Tarland provisioning ecosystem services are prioritised and maintained at the expense of regulating services. The current pathways of environmental change in the East of Scotland will therefore likely benefit food and timber production while impacting adversely on water quality and biodiversity. As the climate changes, the delivery of ecosystem services will be rendered vulnerable at different scales and for contrasting land cover types. This implies for integrated climate change adaptation, a shift towards increased regulating services along with a simultaneous decrease in food productivity may be required in priority areas (Elmqvist *et al.*, 2011).

The EbA approach is highly valuable in assessing the impact of land use options on the delivery of ecosystem services, providing a framework for assessing the trade-offs that are required in land management. Realistically a win-win solution in NFM delivery is not as easily achieved as suggested by the assessment presented in this chapter, but decisions should be aimed at maximizing the benefits whilst minimizing the disbenefits. A systematic approach is needed and land use change needs to be implemented in a controlled step by step manner, with a clear understanding of a catchment's priorities.

8.4 Summary

EbA provides a framework for climate change adaptation strategies using biodiversity and ecosystem service principles. EbA promotes an integrated approach for managing catchments, aiming to deliver multiple benefits. Changes in landscape will affect all ecosystem services in a catchment. An ecosystem assessment was undertaken for the afforestation options at Tarland, to understand what are the expected changes following the implementation of woodland expansion measures, with coniferous and deciduous woodland considered.

The analysis showed that woodland expansion with coniferous woodland will have significant benefits for timber and fibre, business income, flood regulation and carbon storage. However, they will come at a cost for food production as it proposes a land use change involving loss of farmland, and it may decrease the delivery of the ecosystem service associated with recreation (compared to the current land use).

Similarly, increasing the woodland cover with deciduous trees will have positive impacts on the delivery of biodiversity, water quality, soil quality and carbon storage. Negative impacts of deciduous woodland include the loss of available land for food production and a probable loss in business income if productive farmland is lost.

Under different land use scenarios, the delivery of ecosystem services will be closely related to socio-economic drivers that translate into global and local actions shaping the landscape. If food production is a priority (such as for the National Enterprise scenario), a higher food productivity is achieved with costs for biodiversity and water and soil quality. If woodland expansion is desired within upland areas, it may displace some existing semi-natural habitats which will come at a cost for business income from field sports (notably grouse shooting).

Comparing the likely impact of woodland expansion with associated improvements for the existing drainage system, in the delivery of ecosystem services, highlighted the importance of weighting of different services. If an equal weighting is considered for all ecosystem services, then afforestation options could provide a better NFM option for multiple benefit delivery, whilst a higher weighting for the food provision service could shift the balance towards an improved drainage function option.

Win-win solutions promise a beneficial impact on all ecosystem services involved, but by understanding the nature of trade-offs in ecosystem services it becomes clear that win-win situations rarely are possible. The delivery of some ecosystem services will more likely come at a cost for other services. Prioritizing ecosystem services in the catchment is important and could be done by focusing first on existing issues in a catchment by catchment basis.

Chapter 9. Conclusions and recommendations

9.1 Introduction

The research presented in this thesis addressed the knowledge gaps identified in Chapter 1 following the set objectives in Chapter 2. The research used a modelling approach (described in Chapter 4) to assess the effectiveness of NFM options for the current and future climate. In the context of climate change, Tarland Burn catchment was used as a study case (overview given in Chapter 3) to test the impact on water resources of different land use configurations based on varied afforestation percentages, improved drainage systems and socio-economic driven land use scenarios. The changes in the magnitude of extreme weather events were evaluated using extreme value analysis (Chapter 5) with a consideration for the subsequent changes in the stream discharge. Scale and spatial issues were investigated in relation to woodland expansion and land drainage options (Chapter 6) and an assessment was undertaken using UKCP09 climate projections to assess how effective the options will be for the future climate (Chapter 7). An appraisal of the impacts of the NFM options on the potential of ecosystem services was undertaken (Chapter 8) to increase understanding of the underlying trade-offs linked to multiple policy requirements.

9.2 Research approach overview and key assumptions

The project provides a novel approach for investigating NFM options by integrating in a holistic manner the evaluation of the effectiveness of this type of measures not only for the current climate but also for future climate, whilst also considering the likely impacts on ecosystem services. This approach allows for the relative impacts of land use and climate change to be considered together including the assessment of benefits, disbenefits and trade-offs on different ecosystem services. The project used a hydrological modelling approach for the assessment of changes in stream flow. The WaSiM-ETH model was selected for its capacity to adequately represent land use changes (Hölzel *et al*., 2011; Niehoff *et al*., 2002; Verbunt *et al*., 2005) and robustness for climate change investigations (Gädeke *et al*., 2013; Jasper *et al*., 2004). The WaSiM-ETH hydrological model provides appropriate representation of the main catchment processes and it is useful in identifying emerging properties between components. Whilst the link between land use and climate change is very complex, models can be used as a heuristic tool to assess the direction and magnitude of change of discharge response after the implementation of NFM options and to improve the conceptual knowledge of catchment processes. The advantage of using WaSiM-ETH is that (like other physically based models) it can be used to investigate internal catchment processes, which are key in the development of integrated catchment management plans and climate change adaptation strategies (Gädeke *et al*., 2013). The WaSiM-ETH model is currently being used for flood forecasting in the whole of Switzerland and to model the hydrology under climate change for Bavaria, by the Bavarian Environment Agency as part of the KLIWA project.

The modelling approach followed here complements monitoring studies to increasing the understanding of how NFM options can reduce the flood risk at the catchment scale. The modelling results could be further linked with monitoring and site studies. Examples of successfully established NFM monitoring programs include Tarland Burn, Eddlestone, Bedford, Pickering Beck (Archer *et al*., 2013; Gilvear *et al*., 2013; Wilkinson *et al*., 2014).

The Tarland Burn catchment used for the assessment has many of the typical attributes of N-E Scotland which makes it an ideal platform in exploring different NFM options. It has mixed land use and intensive agricultural management with extensive drainage systems implemented historically to lower the water table and reduce waterlogging. The land at Tarland is managed mainly by large estates with tenant farmers. It is also at the transition between the upland and lowland zones, with topography playing an important role for the hydro-climatic regime. There are two villages in the catchment that have experienced consistent floods and the flood risk is expected to increase in the future. The main stream is interesting from a biodiversity perspective as it is a designated Natura 2000 area (EU Habitats Directive).

Another key assumption in the present study was that the assessment of afforestation options were undertaken for fully mature trees, but depending on tree type and tree species, these will require a long time (e.g. 20 years or more depending on tree species) to achieve their highest potential in decreasing the flow peaks. The impacts of plantation age and rotation length was not considered in this project, but their importance in evaluating the impacts of afforestation on water yields is recognized, though these effects are difficult to assess (Best *et al*., 2003).

Furthermore assessing whether improved drainage helps alleviate flooding or increases the flood risk is an over simplification of the processes involved as drainage includes complex local processes. Studies have noted both an increase and a decrease of the flood peaks with drainage, and ultimately the impact is likely to be catchment specific depending on the location of drains and their pattern, soil characteristics and intrinsic hydrological pathways (Blanc *et al*., 2012).

9.3 Summary of the research findings

Chapter 2 provided an overview of the current knowledge relating to climate change, NFM and ecosystem based approaches. The literature review highlighted the need for more research in land use and climate change to provide a better understanding of the expected effectiveness of NFM for the current climate as well as in the future. Previous studies have considered the impacts on high flows as a result of land use changes or climate change, but very few studies have linked these factors together using hydrological models. The present study aimed to address this knowledge gap. Moreover, the assessment of NFM options from an EbA perspective has previously only been considered in separate studies. The present study aimed to provide a holistic approach by linking all these perspectives together using a modelling approach based upon WaSiM-ETH distributed model in the Tarland Burn catchment complemented by a more general ecosystems assessment.

The catchment description chapter (Chapter 3) was drawn from previous studies undertaken in Tarland Burn catchment. Consideration of data collection highlighted issues with the hydro-meterological secondary data sets available, and approaches for data correction were included in the chapter.

Chapter 4 presented the modelling criteria that informed the choice of the model and calibration/validation processes. The discussion emphasized the need for appropriate models informed by the research objectives. This study required the use of a distributed model to be able to capture the influence of spatial land use patterns on the hydrological response. WaSiM-ETH model was selected and model calibration and validation was successfully undertaken. However, there were challenges in interpreting less robust quality datasets as emphasized in this chapter.

The impact of climate change in Tarland was assessed in Chapter 5. The results showed an increase in the magnitude of extreme events for climate projections associated with the medium emission scenario up to the end of the century. However, the extreme value analysis showed larger uncertainties for the large magnitude events suggesting that results should be used with caution in designing adaptation measures. The magnitude of rainfall events of 1 in 100 years could become as large as 1 in 38 year event (19% rainfall total increase) by 2080s. The increased precipitation rates will directly impact on runoff response. The hydrological modelling results show that the magnitude of flood events could increase substantially. By the 2080s, flood peaks could increase by up to 26% for winter antecedent conditions. This has important implications for climate adaptation strategies, especially in communities already vulnerable to floods where there is a need to decrease the flood risk even for the current level of exposure.

Chapter 6 presented the results of the NFM assessment in terms of land use change. Different land use and land management configurations were tested, comprising of afforestation options, drainage and land use scenarios. The results suggested that woodland expansion with coniferous trees had the highest potential to reduce the high flows. This is due to increased interception and evapotranspiration rates compared to deciduous woodland with the differences between coniferous and woodland greatest in the winter when most flood events occur. The flood peak reduction was highest for full afforestation with coniferous woodland, however full afforestation is highly unlikely to occur as catchments like Tarland have crop and livestock functions contributing to local livelihoods and provide food security for Scotland. The assessment of spatial influence on the flood discharge showed a higher reduction for woodland planted in the lowland area (up to a third more for coniferous woodland). This is very important as the lowlands are mainly used for agricultural purposes. Therefore new woodland would have to be integrated with existing land uses (e.g. as riparian or floodplain woodland).

Woodland expansion measures not only decrease the high flows but also the low flows. The impact on the low flows is most pronounced in the summer when the water levels are already low and the interception and transpiration rates are the highest. The results showed that the impact on the low flows is the highest for coniferous woodland. This has important implications for water quality and aquatic functioning especially in catchments where there is already existing low flow problem.

Improved drainage was shown to reduce the high flows by increasing the soil storage capacity, with this achieving a more prominent impact in the summer. The evaluation of improved drainage used a sensitivity testing approach, so the reduction in flood peak could vary between 2.5% and 9.5% depending on the current level of drainage effectiveness in the catchment and the season (more effective in the summer). However most floods occur in the winter so the benefits for flood risk attenuation could become marginal. Moreover the overall impact of improved drainage will depend on a series of factors e.g. soil type, antecedent conditions, drainage density and geometry to name a few.

Land use scenarios based on different socio-economic drivers were tested, and the results showed a larger influence of the type of woodland on the overall impact, compared to just changes in the extent of woodland (i.e. % change). This has implications for forestry policies as deciduous woodland is generally encouraged for multiple benefits (particularly biodiversity) although for flood attenuation coniferous woodland has been found to be more beneficial.

Chapter 7 provided the results of the assessment of the NFM options into the future by linking the land use options with UKCP09 climate projections in the WaSiM-ETH hydrological model. The results suggested that for high levels of afforestation with coniferous woodland, reductions of up to 36% of the flow peaks could be achieved in the winter (for a 1 in 10 year rainfall event) from the current land use for the 2080s. In the summer the reductions could be even higher (of up to 65%) which could exacerbate water quality issues especially as drier summers are expected in most of the UK (Murphy *et al*., 2009). Species selection will be critical for climate change adaptation; Scots Pine and Douglas fir are known to be more drought-tolerant species so could be a better choice for drought vulnerable areas.

The results suggest that climate change will eventually exceed the capacity of beneficial land use change by itself (through NFM measures) to avoid significant changes on catchment hydrology. Only full afforestation in the Tarland Burn catchment with coniferous woodland will be able to reduce the flood risk to the current level of exposure by the 2080s, which is rather an unrealistic option because of the importance of agriculture in local livelihoods. This has important implications as other complementary engineered solutions may therefore be required to counteract the adverse impacts of climate change on flood risk.

Chapter 8 presented the results of the EbA appraisal for the NFM options, using land use maps as a proxy for the supply of ecosystem services. Whilst coniferous woodland is beneficial for flood regulation, carbon storage and fibre/timber, it is less beneficial for recreation, biodiversity and soil quality. Similarly afforestation with deciduous woodland could have a positive impact for biodiversity, water and soil quality and carbon storage but it is likely to bring a disbenefit to business income if it displaces intensive agricultural production systems (particularly arable land). Both coniferous and deciduous will therefore have a negative impact on the delivery of food production service as they involve significant land use change from agricultural land though deciduous woodland does provide some scope for game, berries, honey and medicinal plants (Emery *et al*., 2006).

The results suggested that NFM options may not always be ‘win-win’ solutions as commonly advocated (McShane *et al*., 2011). Instead trade-offs between the delivery of different services may be required and decisions should be aimed at maximizing benefits whilst minimizing the disbenefits. Moreover, for flood protection benefits, the time lags need to be considered. Whilst improved drainage could become effective immediately, woodland expansion option will require more time to become effective. Furthermore the delivery of flood regulation potential as a result of woodland expansion is not currently explicitly linked with other strategies involving land use management. There is scope for a better linkage of these policy initiatives, providing a more integrated approach to land management that includes all ecosystem services.

Historical engineered works (e.g. river straightening, river embankments) undertaken to increase access to the land for farming have reduced the resilience of catchment systems. There is a move now to restore catchments back towards their natural state (Pahl-Wostl, 2007), however full renaturalisation is often not possible especially in places where there is a large concentration of people living in the area. Instead rehabilitation of water bodies to an acceptable standard by using hybrid options may be a better option particularly in urban areas. By using flexible adaptive pathways (Wise *et al*., 2014), the measures can be reviewed and changed to allow for phased adaptive management to be implemented, as more information on hydrological responses from monitoring-networks becomes available.

It is therefore concluded that climate change requires a move away from optimization engineered options to more robust NFM options that may be developed as complements to engineered schemes. Optimization schemes do not allow for flexibility, being locked into rigid solutions that cannot be adapted as conditions change. By contrast, robust schemes are by nature more adaptable and cover more scenarios for an uncertain future. NFM options are more flexible and can be used as alternative or complementary strategies to alleviate at least some of the risk and retain flexibility. Researching NFM options allows for a screening of different options, identifying which are more suitable for certain catchments (e.g. woodland expansion options may be unsuitable to areas in the West of Scotland due to a priority for peatland restoration). NFM options could be assessed for their suitability based on catchment typology including topography, if they are fast or slow responding catchments, catchment shape and socioeconomic pressures (e.g. land use and population changes).

The threat posed by climate change means that risk cannot be completely engineered out of the system but different options can be used to increase the resilience of catchments to adverse impacts of future climate (both expected and unexpected). The choices about land use should also have at their core an enhancement of landscape resilience. The EbA approach increases the catchment's resilience to buffer extreme events, representing a good insurance strategy for the unexpected whilst also aiming to provide multiple benefits for society. The EbA allows for the exploration of trade-offs and cross-cutting risks and it is useful in avoiding maladaptation (i.e. a short-term response that exacerbates future risks), by providing an integrated approach for the assessment of NFM options. It is therefore concluded that the EbA approach has great potential considering climate change risk, and should be further considered by policy makers in land use decision making.

The results of the current research can be assessed beyond the specificity of Tarland and can be useful to inform decision making around flood risk management in other catchments in UK and at a wider European scale. However, the model selected is not able to capture very small scale local interventions currently being tested in a few UK catchments (Nicholson *et al*., 2012). Other approaches may be required for assessing the catchment behavioural differences due to lags in the system after the implementation of land use options, for example using data-based mechanistic modelling (Beven *et al*., 2012). This employs advanced complex statistical procedures to infer the model structure from empirical data in an inductive manner.

Whilst modelling approaches have been widely used over a wide number of applications there are several sources of uncertainty, running from the input data to the model assumptions that need to be acknowledged in the assessment of the results. The

WaSiM-ETH modelling are presented in a deterministic manner rather than as a probability range. Whilst models are limited in their representation of complex real-world systems, they can be used to learn about the catchment and the impact of different land use management options on hydrological behaviour. By linking with monitoring studies the model can be further refined and tested, thereby increasing the confidence in the results.

The future is fundamentally uncertain. Large differences exist between the projections of different climate models, which means that the number of people at risk of flooding is also very uncertain (Arnell *et al*., 2010). The UKCP09 projections aim to incorporate climate uncertainties by providing probabilistic ranges rather than deterministic outcomes, but uncertainties still exist especially as they are guided by expert opinion of key parameters (Murphy *et al*., 2009). Whilst there is no guaranteed way to accurately predict an uncertain future, models are useful in representing the conditions for the current climate to help us prepare for the future.

Drawing to a conclusion, linking land and climate change together gave important insights into how land use might impact runoff response in the future. Climate change adaptation needs to consider that climate impacts may eventually exceed any existing land use option (no matter how extensive) so other flood attenuation measures should be considered in addition to NFM (e.g. small-scale environmental engineering). The choice of the distributed modelling tool was justified by the results as it allowed the investigation of spatially distributed land use patterns in relation to runoff generation showing how planting woodland in the lowlands is more beneficial for flood risk attenuation. Moreover differences in the results for different land configurations showed that the spatial distribution of land use measures plays an important role and should be considered in this type of assessments. The EbA analysis shifted our thinking that NFM options are universal win-win solutions to understanding that trade-offs are required and decisions need to be made based on reconciling both local and national priorities.

9.4 Policy implications of the research

The present study increased understanding of whether NFM options can help attenuate the flood risk for current and future climates, and contributed to the wider body of knowledge of how land use can be used more effectively for climate change adaptation.

Currently there are more grants available for afforestation programs with deciduous woodland, though the current research showed that coniferous woodland has substantially higher benefits for flood risk protection. Moreover, the results demonstrated that planting woodland in lowland areas achieved considerably higher flow peak reductions. However this could potentially conflict with other agricultural priorities as the extended floodplain often provides the most fertile agricultural land for crops because of the alluvial soils (assuming they are well drained). Thus, extensive afforestation may not be possible in the lowland under the current priorities, though smaller patches of woodland in the lowland could still be beneficial for flood risk as well as for other purposes (e.g. shading for cattle).

Currently no government grants are being given for the maintenance of artificial drains and farmers need to cover the maintenance costs themselves (Defra, 2012b). Whilst many drains are typically observed to be generally working well, some of them may be blocked and not fully functional based upon their original design objectives (O’Connell *et al*., 2007). The modelling results showed that by properly designing and maintaining the drains a reduction of the flood risk could be achieved. Including drainage maintenance with other agricultural schemes could benefit the flood risk management in catchments.

Appropriate incentives schemes for NFM uptake by farmers at a local scale have been identified as one of the barriers to NFM implementation by Holstead *et al*. (2014). Others barriers include a lack of support and advice that is tailored to each specific context and farmer’s views, public perception of NFM options and local traditions (especially for farm owners). Moreover, the lack of an integrated approach for flood risk where all sectors share responsibility has been expressed as a concern along with the limited inclusion of NFM with other farming payment schemes (Holstead *et al*., 2014). Currently the flood risk alleviation potential for woodland expansion is not included consistently in afforestation programs. The implementation of NFM schemes would benefit from a better connection with other existing policies e.g. water quality, urban planning and biodiversity (Holstead *et al*., 2014; Rouillard *et al*., 2015). The revision of the WFD and CAP reforms provide an opportunity for including the flood risk potential in agricultural and water policies (Rouillard *et al*., 2015).

The present study also highlights that weighting of different ecosystem services will guide the implementation of land use options for the delivery of certain services. The weighting will be guided by the targets set for Scotland by policy makers. Moreover there is a need for a common framework in evaluating and mapping ecosystem services to develop robust economic, ecological and social values of ecosystem services for policy uptake at a national level in land use decision making (Crossman *et al*., 2013).

Many uncertainties still exist and more research is needed in creating better future projections and system representations. Policy uptake requires greater evidence that NFM measures work, but that definitive evidence base may take many years to develop, which may be time we do not have because the best evidence suggests that flood risk is increasing. Scientific progress may therefore be too slow for policy development and in some cases it is not able to catch up with the policy needs and the lead time required for implementation. There is therefore a need to make decisions based on limited information but also on the best current level of knowledge, which is best achieved by developing strategies that are flexible and can be adjusted as new data becomes available. This adaptability is one of the key features of NFM measures together with their multiple benefit delivery potential for other policy objective.

9.5 Further research

Different opportunities to take this research further have been noted below:

Modelling

- Improving the sub-surface representation in the WaSiM-ETH hydrological model by including the macropores module and spatial representation of the surface roughness
- Investigating the impact of tree age on the runoff response for different woodland types (i.e. coniferous and deciduous)
- Linking hydrological modelling to hydraulic modelling based upon surface roughness

Field-work

- Linking the hydrological modelling approach with a monitoring study to test the findings against a field case study

- Expanding the current analysis by undertaking field measurements of land use parameters for different woodland types (i.e. coniferous and deciduous) linking them with soil types for common trees in Scotland to test the modelling results
- Further field measurements for measuring the hydraulic conductivity of different representative soil types and testing the influence of land use on this parameter

Stakeholder-engagement

- Engaging the farmers in the catchment to see what is their attitude towards the implementation of the NFM tested for the present study (i.e. woodland expansion and drainage improvement) and identify best ways to take this forward

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Appendix A

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Evaluating wider benefits of natural flood management strategies: an ecosystem-based adaptation perspective

Oana Iacob, John S. Rowan, Iain Brown and Chris Ellis

ABSTRACT

Climate change is projected to alter river flows and the magnitude/frequency characteristics of floods and droughts. Ecosystem-based adaptation highlights the interdependence of human and natural systems, and the potential to buffer the impacts of climate change by maintaining functioning ecosystems that continue to provide multiple societal benefits. Natural flood management (NFM), emphasising the restoration of innate hydrological pathways, provides important regulating services in relation to both runoff rates and water quality and is heralded as a potentially important climate change adaptation strategy. This paper draws together 25 NFM schemes, providing a meta-analysis of hydrological performance along with a wider consideration of their net (dis) benefits. Increasing woodland coverage, whilst positively linked to peak flow reduction (more pronounced for low magnitude events), biodiversity and carbon storage, can adversely impact other provisioning service – especially food production. Similarly, reversing historical land drainage operations appears to have mixed impacts on flood alleviation, carbon sequestration and water quality depending on landscape setting and local catchment characteristics. Wetlands and floodplain restoration strategies typically have fewer disbenefits and provide improvements for regulating and supporting services. It is concluded that future NFM proposals should be framed as ecosystem-based assessments, with trade-offs considered on a case-by-case basis.

Key words | ecosystem-based adaptation, ecosystem services, natural flood management, trade-offs

Oana Iacob (corresponding author)
John S. Rowan
Centre for Environmental Change & Human Resilience,
University of Dundee,
DD14HN,
UK
E-mail: *o.iacob@dundee.ac.uk*

Iain Brown
The James Hutton Institute,
Craigiebuckler,
Aberdeen,
AB15 8QH,
UK

Chris Ellis
Royal Botanic Garden Edinburgh,
20A Inverleith Row,
Edinburgh,
EH3 5L,
UK

Oana Iacob
John S. Rowan
Iain Brown
Chris Ellis
ClimateXChange,
15 South College Street,
Edinburgh,
EH8 9AA,
UK

INTRODUCTION

The global climate is expected to change at a rate unprecedented in human history, as exemplified by rising sea levels, glacial retreat, changing precipitation patterns and an increasing frequency of extreme weather events (Kiehl 2011). Evidence for these changes, which include both short-term climatic variability and longer term trends, underpins the need for a twin-track response, involving both mitigation and adaptation strategies (Perez *et al.* 2010). With regard to adaptation, the primary goal is reduced exposure to natural hazards such as flooding whilst increasing human resilience to hazard-related events from the local scale upwards (Tschakert & Dietrich 2010). Evidence increasingly demonstrates that local flood risk must be viewed as non-stationary. Risks vary in direct response to changing hydroclimatic drivers but also to indirect controls on runoff generation and flow routing as a consequence of catchment land use changes and hydromorphological alterations to the channel network (Werritty *et al.* 2006).

Traditional approaches to flood control have emphasised 'hard' engineering 'solutions', mainly centred around protection of high value infrastructure, but also more widely emplaced to defend agricultural production on drained wetlands and floodplains. These schemes often have significant environmental impacts because they disrupt natural flow and storage processes. Moreover, whilst engineered strategies are generally designed to provide protection for specific flood levels (with inferred recurrence intervals), maintaining the same level of cover under changing climatic

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conditions requires upgrading (potentially repeatedly) with attendant economic, social and environmental costs. Thus there is a pressing need to develop improved adaptation strategies centred on sustainable natural resources and for catchment land-based flood management measures promoting greater resilience against the anticipated increased frequency of extreme events (Heller & Zavaleta 2009; Campbell *et al.* 2009).

Ecosystem based Adaptation (EbA) is an emerging paradigm for managing natural resources under increasingly variable and perturbed climatic conditions. As an approach it includes 'soft' and 'hard' responses in the form of targeted ecosystem conservation, management and restoration actions (Jones *et al.* 2012). EbA therefore aims to enhance the natural dynamic and resilient properties of ecosystems to buffer the adverse impacts of climate change and therefore reduce human vulnerability (Colls *et al.* 2009). The need for interdisciplinary perspectives, including social science, in adaptation planning was emphasised by Heller & Zavaleta (2009). In particular, EbA recognises that future change is intrinsically uncertain due to climate change and associated pressures (e.g. spread of invasive species), and that the most effective strategies to reduce risk therefore include measures to improve system resilience rather than being predicated on a particular outcome.

The focus in this paper is to assess the utility of EbA as a framework for guiding natural flood management (NFM) strategies. NFM is widely recognised as an option to reduce flooding whilst achieving multiple benefits throughout the catchment and is rising rapidly up the policy agenda across Europe because of its potential to buffer the effects of climate change (Wheater *et al.* 2010). Traditional hard (and indeed soft) engineering solutions are generally location specific measures applied to protect social and infrastructural assets at risk of flooding. These measures are designed to provide protection for certain flood events under assumed stationarity in magnitude/frequency relations (Figure 1(a)). Clearly, they become less effective, i.e. risks increase, under non-stationary conditions symptomatic of climate change (Figure 1(b)). By comparison, the introduction of NFM measures potentially provides greater adaptive capacity to negate climate change by re-naturalising flows or at least provides a buffer against subsequent regime changes (Figures 1(c) and (d)). However, the performance of NFM will ultimately be dependent on

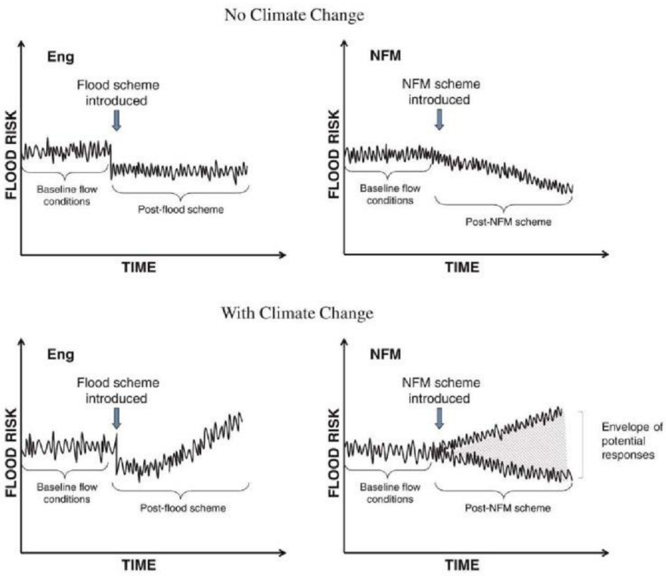


Figure 1 | Representation of expected engineered (Eng) and NFM strategies behaviour in no climate change conditions and with climate change.

specific site conditions, inclusive of landscape setting, catchment characteristics, the degree of hydromorphological alteration and the extent and appropriateness of the different measures adopted. Performance will also evolve or mature over time, meaning that flood risk should be constrained within an envelope of possible outcomes (Figure 1(d)) rather than based upon a specific deterministic outcome.

NFM involves the utilisation or restoration of 'natural' land cover and channel-floodplain features within catchments in order to increase the time to peak and reduce the height of the flood wave downstream (Environment Agency 2010). This may involve altering multiple elements of a catchment water balance by promoting interception, infiltration and groundwater storage, enhancing water losses through evapotranspiration, lengthening hydrological pathways and increasing flow resistance. In terms of scale, NFM measures are typically evaluated at the catchment scale, consistent with concepts of whole-system planning (Figure 2(a)), though specific actions may be more local, depending on catchment size, levels of stakeholder acceptance and governance arrangements. Figure 2(b) seeks to show, at least in a qualitative way, the relative differences in the invested capital and net benefits of different flood control strategies, illustrating that costs are typically highest in relation to hard-engineering infrastructure protection. NFM schemes, and more systemically EbA, capitalise on the regulating services of natural systems in terms of flow regulation and flood control but can also realise significantly greater co-benefits. Hence the benefit-to-cost ratio is potentially much more favourable for these schemes, as would be represented in a total economic evaluation, although rarely accounted for in conventional assessments. On the other hand, while engineering schemes provide increased flood protection from the day of completion, NFM schemes generally involve a lag time to establish. NFM performance also tends to be less certain because comparable interventions on different hillslope, channel, wetland or floodplain features can produce complex and dynamic response and divergent outcomes at the catchment scale in relation to runoff and sediment production (Schumm 1979; Chorley et al. 1984; Scottish Environment Protection Agency (SEPA) 2012).

This paper aims to provide a better understanding of NFM approaches and their potential role as a climate change adaptation strategy using the ecosystem services (ESS) framework (UK National Ecosystem Assessment (NEA) 2011). The meta-analysis, drawing on monitoring and modelling data from 25 (mainly) European studies, was used to explore the links between afforestation extent and flood risk downstream. A comparative analysis of different NFM strategies was also undertaken using an ESS framework revealing positive and negative impacts on goods and services and providing the basis to consider options and trade-offs in terms of decision-making by catchment managers and wider stakeholder groups. The study does not include the full range of NFM options but provides a foundation for further investigation.

METHODS

The evaluation framework for the current study was drawn from the UK National Ecosystem Assessment (NEA). This is

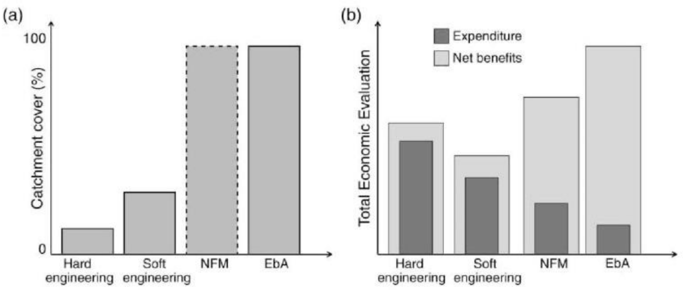


Figure 2 | The relationship between different approaches for flood risk management: (a) size on which they are being implemented, (b) the financial means engaged in the implementation of these approaches including potential benefits.

the first systematic assessment of goods and services provided by the natural resources underpinning the UK economy (UK NEA 2011). Building on the global Millennium Ecosystem Assessment (MA), the NEA distinguishes between provisioning, regulating, cultural and supporting services. These services are further divided into 'final ESS' (e.g. water purification) that directly contribute to the tangible goods that are valued by people and 'intermediate ESS' (e.g. nutrient cycling) that underpin these final ESS, but not directly linked to goods. For the present purposes only final and intermediate ESS were considered, and not the goods or beneficiaries which are often associated through complex human systems.

The significant adverse impacts were noted with a '- -', whilst the less significant ones with a '−'. Similarly a '+ +' was assigned for significant positive impacts and '+' for less significant improvements. If there were no changes in the initial state of the ESS a '0' value was assigned and a 'NA' (Non-Applicable) was assigned if certain ESS were not represented in a particular catchment. The scoring process was informed by evidence from the literature and expert-judgement tested between the authors. The high level of internal agreement suggests that the direction and scale of impacts is a sound first approximation.

STUDY CASES

Twenty-five study catchments were compiled for this project drawn from the review in Scotland of Price *et al.* (2011) and other examples from the wider academic literature. Most of the study cases are based in the UK, other studies being located in mainland Europe and New Zealand (Figure 3). Consistent with Price *et al.* (2011) four categories of NFM schemes were recognised: (a) (re)establishment of forests and woodland; (b) drainage and drain blocking; (c) wetlands and floodplains restoration; (d) combined measures.

The case-study catchments differed greatly in size, spanning four orders of magnitude from 10,000 km^2 to under 1 km^2 (see Table 1). Two alternative methods were used to assess the effectiveness of different NFM proposals: (i) hydrologic and hydraulic modelling exercises to assess flood attenuation potential and (ii) direct monitoring. The variation in scale and lack of consistency in assessment

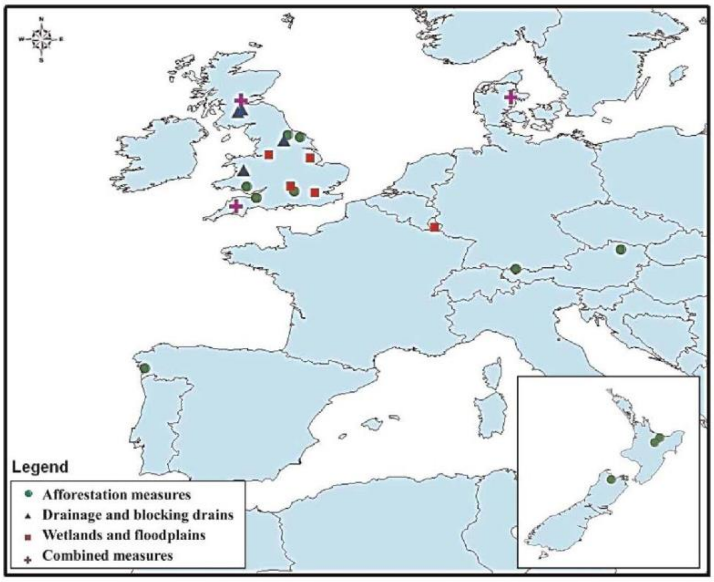


Figure 3 | The locations where the selected projects have been implemented, by NFM categories.

Table 1 | General information for the selected studies

No	Catchment name and type of NFM scheme	Country	Area (km^2)	Approach	Reference
Forests and woodland					
1	Trent, Severn, Thames	England	10,000	Modelling	Naden *et al.* (1996)
2	Parrett	England	1,675	Modelling	Park *et al.* (2006)
3	Iller	Germany	954	Modelling	Francés *et al.* (2008)
4	Tarawera	New Zealand	906	Monitoring	Dons (1986)
5	Kamp	Austria	622	Modelling	Francés *et al.* (2008)
6	Poyo	Spain	380	Modelling	Francés *et al.* (2008)
7	Laver	England	79	Modelling	Nisbet & Thomas (2008)
8	Cary	England	77	Modelling	Thomas & Nisbet (2006)
9	Pickering Beck	England	66	Modelling	Odoni *et al.* (2010)
10	Pontbren a,b	Wales	4	Modelling	Wheater *et al.* (2010)
11	Parukohukohu	New Zealand	~0.29	Monitoring	Dons (1981)
12	Moutere	New Zealand	~0.06	Monitoring	Duncan (1995)
Drainage and drain blocking					
13	Llanbrynmair	Wales	3	Monitoring	Leeks & Roberts (1987)
14	Coalburn	England	1.5	Monitoring	Robinson *et al.* (1998)
15	Blacklaw Moss	Scotland	0.07	Monitoring	Robertson *et al.* (1968)
16	Ripon	England	120	Modelling	JBA (2007)
17	Ballard study	England	0.2	Modelling	Ballard *et al.* (2010)
Wetlands and floodplains					
18	Steinsel	Luxembourg and France	2	Monitoring	Liu *et al.* (2004)
19	Sinderland Brook	England	2	Monitoring	Environment Agency (2010)
20	Quaggy	England	–	Monitoring	Potter (2006)
21	Cherwell	England	–	Modelling	Acreman (1985)
22	Long Eau	England	–	Monitoring	Moss (2007)
Combined measures					
23	Lilea	Denmark	–	Monitoring	Hansen (1996)
24	Glendey	Scotland	2	Modelling	Johnson (2007)
25	Tillicoultry River	Scotland	–	Modelling	Johnson (2007)

methods present challenges when evaluating the performance of different NFM measures, but these differences do not substantially affect the qualitative ESS analysis undertaken here.

PERFORMANCE OF NFM MEASURES

The performance of the NFM measures was presented in the original studies in different ways: (i) as flood peak reduction for different flood event return periods (e.g. 1, 2, 25, 50, 100 years), (ii) as increase in time to peak or (iii) as a decrease in annual probability of flood risk for the area (see Table 2). Baseline and catchment data were also presented in a wide variety of styles and completeness presenting further uncertainties in comparing the relative performance of different NFM schemes (cf. Naden *et al.* 1996; Wheater *et al.* 2010). Consequently, the analysis mainly explores the relationships between afforestation projects and their impact on floods of different recurrence interval, for example, distinguishing between small and frequent floods (<2 years) versus much larger and rarer floods (50–200 years). For studies reporting

Table 2 | Indicators of NFM actions in reducing the flood risk in the selected study cases

Categories	Type of measurement
Forest and woodland	Peak flow reduction Time to peak
Drainage and drain blocking	Time to peak Factor of unit hydrograph Percentage of runoff
Wetlands and floodplains	Peak flow reduction Time to peak Annual probability of flooding Water volume
Combined measures	Peak flow reduction Water volume Water velocity

flood peak reduction in terms of envelope ranges we have used the mean or mid-range value for reduction performance. The role of catchment size was also investigated.

The relationships between afforestation extent and flood peak attenuation for two return period groups is shown in Figure 4. The baseline vegetation varies among the studies, some documenting an increase of tree cover replacing grassland, pasture, arable land, mixture of scrub and non-irrigated trees whilst for others it is not stated. These relations are clearly non-linear and statistically significant ($r^2 = 0.52$, $p < 0.001$) for small magnitude events but also for larger events ($r^2 = 0.61$, $p < 0.05$). The higher exponent for the <2 year floods means that the greatest attenuation potential occurs for the smaller events achieving predicted flood peak reductions approaching 60–70% as complete forest coverage is attained. The effects are less pronounced in the case of the larger events, where woodland coverage of c. 80% was reported to effect a 30% reduction in peak flow values.

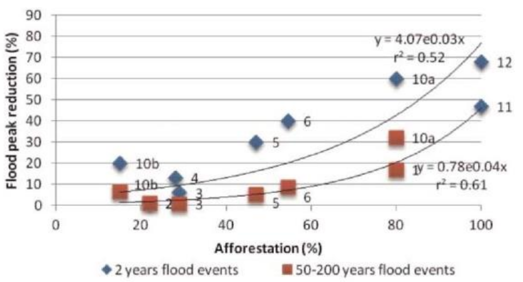


Figure 4 | The relationship between the percentage of several afforestation strategies and their performance for small and large events (labels refer to catchments in Table 1).

Across the magnitude-frequency range shown in Figure 4 afforestation is shown to deliver 'benefits' in terms of flood attenuation, especially in those catchments where woodland cover was initially low. However, the results also clearly point to threshold conditions in the full continuum of events beyond which NFM and ultimately hard engineered solutions will be overwhelmed and extensive flood damage is inevitable.

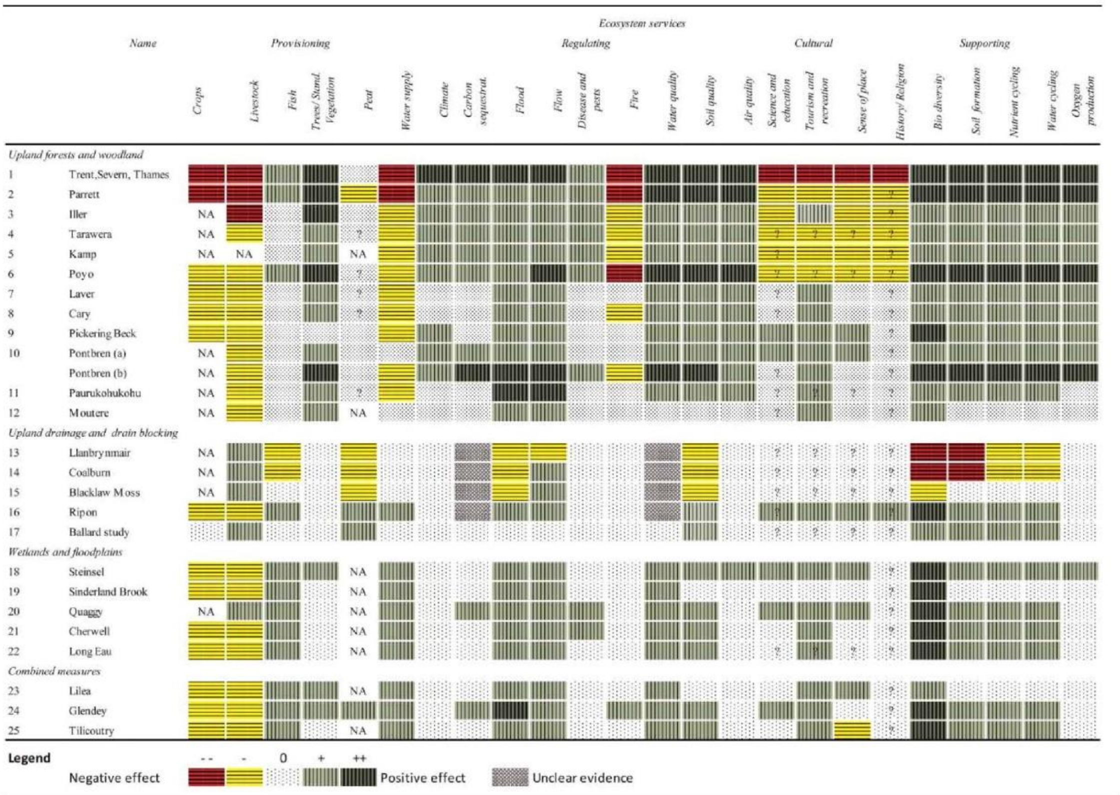
Recent analysis has also established that NFM cannot be universally considered as a 'no regret' measure (i.e. benefits will exceed costs in all circumstances) in adaptation terms. Odoni & Lane (2010) demonstrated that NFM can in certain circumstances synchronise previously de-coupled sub-basin flood peaks and consequently aggravate downstream flooding problems. This further highlights that NFM measures are more effective in some locations than others. Deciding the best location for NFM measure implementation can be rather complex and will generally require detailed modelling and good calibration data similar to hard engineering schemes.

ECOSYSTEM SERVICE ASSESSMENT

The ecosystem approach provides a framework for evaluating NFM options both in terms of their primary goal of catchment runoff control, but also more systemically in relation to ecosystem function and the delivery of wider goods and services. NFM targets, such as reducing flood peak height and extending time to peak, are examples of response metrics resulting from specific land management interventions. Here the related (direct and indirect) consequences are assessed for different groups of ESS using scores ranging from 'significantly adverse' to 'significantly positive' impacts (Table 3). Some services, such as biodiversity, arguably span several columns but for clarity we here attribute positive/negative impacts to the single most important category for each NFM project considered. Within the table, question marks accompany those scores where the case-study background information was restricted and so acknowledges a greater level of uncertainty.

Increasing the coverage of 'forests and woodland' in upstream areas was convincingly shown to reduce downstream flood peaks and base-flows in the Polo, Iller and

Table 3 | ESS assessment



Parrett catchments. Some projects focussed specifically on establishing riparian or floodplain woodland, for example, Pickering Beck, Cary, Laver but for both groups as tree cover increases, the negative consequences on 'Crops' and 'Livestock' services rise as a result of less land being available for those services. Those catchments, such as Tarawera, Kamp, Pontbren, with a proportionately small arable footprint limited the loss of food production to 'Livestock' service. By contrast the 'Trent, Severn and Thames' and Pontbren case-studies had the most significant negative effects on these agrarian ESS, as both proposed complete coverage of woodland. These comparisons highlight that both the scale of the measure and the size of the area on which the measure is being implemented play a key role when assessing system responses.

Increasing tree cover in the Pontbren, Poyo and Kamp studies had multiple hydrological consequences as quantified through the catchment water balance. Over time trees develop a complex root system (growing and dying) creating preferential pathways for water flow and promoting higher infiltration rates (Archer *et al.* 2002; Schwärzel *et al.* 2012). Combined with higher rates of interception and evapotranspiration it results in reduced runoff and sediment production, the effectiveness of which diminishes as storm intensity increases (Calder 1990). Over time biogeochemical cycling dynamics changed, promoting greater carbon sequestration and reduced nutrient efflux (subject to woodland species composition), with the potential to significantly augment biodiversity and soil and water quality

(Hastie 2003). The largest gains in ESS were reported for those studies involving a significant increase of tree cover with a diverse forest structure.

If trees are planted on organic-rich and peat soils deeper than 20–40 cm, there can be a negative impact on 'carbon sequestration' services as a result of elevated mineralisation rates (Cannell 1999). Most of the studies did not give a full characterisation of soil properties and this impact was therefore hard to quantify. Increasing the tree cover percentage will have mixed impacts on 'Tourism and recreation' services. Whilst for relatively small increases it would likely have a positive impact, for significant afforestation increases a negative impact may result from limited and restrictive access (assuming that the afforestation is fast-growing coniferous plantations). The Parrett catchment has important cultural assets (Postchin et al. 2008) thus a 22% afforestation as proposed in the study would be likely to have negative impacts on key features of the cultural landscape such as 'History', 'Education' and 'Sense of place'.

Studies which addressed actions in the 'Upland drainage and drain blocking' category were based both on monitoring and modelling approaches (e.g. Robertson et al. 1968). Upland drainage options were historically implemented to improve land quality for enhanced agricultural, forestry or game bird productivity (Burt 1995). The method is documented as having significant adverse impacts in terms of runoff response. In the three studies included herein, although the evidence is variously reported (e.g. time to peak, runoff response) they all point to a flashier response and higher flood peaks. Robertson et al. (1968) and Robinson et al. (1998) documented reductions in 'time to flood peak' parameter for the Blacklaw Moss and Coalburn studies, while Leeks & Roberts (1987) recorded a much peakier runoff response for the Llanbrynmair following land drainage. Therefore, although lowering local water tables on the land can improve grazing potential and stocking capacity, reference to the ESS framework suggests that these benefits may come at the expense of increased erosion and carbon loss in organic-rich upland soils. Water quality also typically declines due to increased colour and higher sediment-associated nutrient fluxes (Table 4).

Drain blocking strategies are generally considered to have positive effects on ESS, inclusive of flood peak reduction (JBA 2007; Ballard et al. 2010). Whilst Ballard et al. (2010) assumed no vegetation change after drain blocking in their model, the present analysis explicitly considered this effect. As the ecosystem integrity of soil and vegetation recovered, its physical cohesion increased and erosion rates declined (Holden et al. 2007). The effects in relation to carbon storage and water quality were however more mixed (Table 4). Whilst some studies showed a significant reduction in pore water dissolved organic carbon (DOC) and the level of discolouration (Armstrong et al. 2010), others have suggested the method is inefficient (Glatzel et al. 2003; Wallage et al. 2006). The norm linking drain-blocking to decreased peak runoff rates has exceptions, for example, vegetation-filled drains in peat-rich soils if this blocking results in faster overland flow rates over less vegetated surfaces (Ballard et al. 2012). Overall, evidence for the efficacy of upland drain blocking remains equivocal, varying with local conditions, drain spacing, and the availability of unsaturated water storage capacity (Robinson 1990). The time lag may explain some of these contradictory findings however they are not explicitly described in the original studies thus these differences could not be fully explained.

The restoration of wetlands and floodplains was assessed for five studies. In all cases the focus was on the operational phase and thus discounted the initial restorative-engineering phase. The Cherwell and Sinderland Brook studies both aimed to re-connect the channels to their floodplains, resulting in minimal land use change, but important gains in connectivity, water storage and runoff response. The Quaggy River project proposed floodplain restoration through culvert removal, whilst the Steinsel study aimed to rehabilitate the river basin by planting, changing riparian and in-stream vegetation and by re-meandering the channelised reaches. Negative impacts in relation to crop and livestock production were minor, whereas significant positive benefits were registered for biodiversity, fisheries and wider amenity value. Reinstating the overbank flow storage capacity of the floodplain will yield a positive effect for 'Water supply' and 'Flood regulation' due to enhanced buffering of the response of low and high flows to precipitation variability.

The last category under consideration examined combined NFM measures and their cumulative effects. As this involves a wider range of strategies, including the

Table 4 | Changes in stream chemistry following the drainage and drain blocking

Action taken	Water quality parameter	Direction of change	Author	Location	Soil type
Drainage	DOC	Increase	Freeman *et al.* (1993)	Laboratory	Peat rich soils
		Increase	Glatzel *et al.* (2003)	Quebec, Canada	Bog
		Increase	Wallage *et al.* (2006)	River Wharfe, UK	Blanket peat
		Decrease	Moore (1987)	Sept Iller, Canada	Bog
		Decrease	Chapman *et al.* (1999)	Rivers Wye and Severn, UK	Mixed upland of peat, stagnopodzols and stagnogleys
		Decrease	Chapman *et al.* (2005)	Upper Teessdale, UK	Deep peat
	Organic carbon	Increase	Lundin & Bergquist (1990)	Torvbraten, Sweden	Peatland
		Increase	Wallage *et al.* (2006)	River Wharfe, UK	Blanket peat
		Decrease	Nilsson & Lundin (1996)	SW Sweeden	Dissected peatland area
Blocking drain	DOC and Water discoloration	Increase	Glatzel *et al.* (2003)	Riviére du Loup, Canada	Peatland
		Increase	Worrall *et al.* (2007)	Whitendale, UK	Blanket peat
		Decrease	Wallage *et al.* (2006)	River Wharfe, UK	Blanket peat
		Decrease	Armstrong *et al.* (2010)	Catchments across UK	Peat soils

interactions between them, the co-benefits were expected to be high. The Lilea study (Hansen 1996) sought to control discharge whilst re-establishing flow continuum thereby ensuring free passage to fish (e.g. introducing a two-stage channel section and planting riparian trees). Although these actions involved small land use changes, the enhanced environmental quality provided important 'Biodiversity' and 'Recreational' benefits. The Glendey study (Johnson 2007) investigated the realignment of an artificial water course into a meandering channel and the restoration of the wetland (drain blocking and the planting of tree barriers across the wetland). The scale of the interventions at this site (c. 2 ha) are small in relation to the whole catchment (2 km^2), but yield disproportionally positive benefits because of their functional significance (e.g. water quality and biodiversity gains within small but important wetland patches). The only adverse effects were expected to be on 'Crops' and 'Livestock' due to land use change. In the Tillicoultry system (Environment Agency 2010) multiple measures were introduced including meander restoration to improve habitat quality, reducing the need for channel bank maintenance. This had also increased cultural value through aesthetic improvements and angling potential. The threshold of significance when multiple small localised interventions express themselves cumulatively at the catchment scale, particularly in consideration of complex response, is a key issue in hydromorphological research (Fullerton *et al.* 2010). Cumulative benefits or multiple actions are likely to outweigh disbenefits and hence coordinated action-packages are recommended rather than individual or localised actions to realise the full potential of integrated catchment management.

DISCUSSION

In a stationary climate, NFM measures are generally ascribed more uncertainty as compared with traditional engineering approaches to flood control. Under changing climate conditions such distinctions become blurred. Traditional measures typically focus on water level control in relation to the protection of specific assets but less attention has been given to flow generation and downstream routing dynamics. The few reliable instrumented catchment studies available span a range of hydroclimatic, landscape and local geomorphological controls, which makes up-scaling from the specific to the general highly challenging. Consequently extrapolating to new situations is a major source of uncertainty in applying NFM.

In addition the impact of an increased percentage of tree cover is not limited just to the afforested zone. Particularly for riparian woodland the interactions between terrestrial and aquatic ecosystems will lead to alterations of nutrient inputs, changes in micro-climate and contribution of organic matter to the stream and floodplain, and retention of inputs (Gregory *et al.* 1991). The change may therefore provide benefits such as 'Climate regulation' and 'Biodiversity' outside the afforested area.

To date the ESS assessment has not explicitly considered the significance of a non-stationary climate. However, it is acknowledged that climate changes, expressed in terms of systemic trends (e.g. warmer/wetter winters, hotter/drier summers, increased variability and changing magnitude/frequency of events) will also play out in relation to runoff and water quality effects (reflecting altered biogeochemical processes) and land management choices driven by dynamic policy influences.

Moving forward the selection of NFM strategies should consider both local catchment and wider exposure to climate changes, situating NFM as a central component of EbA (Colls *et al.* 2009; Perez *et al.* 2010; Jones *et al.* 2012). For example afforestation measures are not recommended in areas where drier summers are projected to occur, as trees directly impact on the water yield and may exacerbate existing drought problems (cf. Ray 2008). Ensuring the climate-readiness of NFM options requires context specific information taking into account climate change predictions and further acknowledging how different choices will play out under alternative socio-economic scenarios (cf. Brown *et al.* 2008; Dunn *et al.* 2012).

The performance of afforestation measures in reducing the flood peak depends on several factors, notably the previous land use. Runoff reductions are likely to be larger and more sustained for afforestation from grassland compared with afforested shrubland (Farley *et al.* 2005). Other studies report a higher infiltration rate (up to 60 times more) for young native woodland shelter-belts compared to grazed pasture (Bird *et al.* 2003; Eldridge & Freudenberger 2005). The performance is also dependent on the tree species selection (Farley *et al.* 2005). Species composition and planting style also influence biodiversity gains with the greatest benefits associated with diverse land use schemes that provide mixed habitats (depending on patch sizes, composition and connectivity). Scale is another fundamental challenge to the assessment process and the examples here span four orders of magnitude within the same NFM category. Theoretically a larger catchment area has the potential to achieve greater benefits in relation to nationally significant issues such as biodiversity and food production (Hein *et al.* 2006).

A key point to be emphasised is the evolutionary nature of NFM measures and the lag times in relation to consequent effects on runoff response, which should therefore be considered in NFM planning. This relationship is dynamic and susceptible to change over time. Similarly, the relationship between the NFM measure and the co-benefits for ESS is dynamic, and there are often significant time lags to be considered particularly for the other regulating services in addition to flow regulation (e.g. C sequestration, water quality). For example as forest systems mature they have an increasingly strong effect on the environment around them, and their benefit for some of the ESS will increase with time, for example, carbon storage (Andréassian 2004). Farley *et al.* (2005) noted that streamflow response to afforestation is anticipated to be very rapid (within 5 years of planting) with maximum runoff reductions achieved between 15 and 20 years after planting. This was investigated across a wide range of climatic conditions mostly for pine and eucalyptus afforestation. A similar response was recorded by Scott & Lesch (1997) for South Africa's Mokobulaan catchment. Completely afforesting the catchment with eucalypts was noted to decrease significantly the stream flow after three years of planting, stopping it all together after nine years. The same afforestation with pine trees produced a significant decrease in the fourth year and dried up the stream completely after 12 years.

CHALLENGES OF AN ESS ASSESSMENT

Examining the relative merits of different NFM schemes from an ESS perspective presents many challenges. The impact on 'Cultural Services' was particularly difficult to assess as limited information was typically provided in this regard and the implications for cultural services are often strongly dependent on the current context (e.g. past and present land use patterns). In some cases (e.g. Thames, Trent, Severn, Parrett) finding alternative sources of information was relatively easy, but for the smaller catchments this was rarely the case. Afforestation measures will impact the

'Tourism and recreation' service differently depending on the type of forest (i.e. commercial forest or natural woodland restoration). Natural woodland restoration will enhance the 'Sense of place' and bring benefits for 'Tourism and recreation' whilst commercial forest is expected (depending on local conditions) to have no impact or an adverse impact. Moreover the percentage of afforestation cover plays an important role in the assessment for 'Cultural Services'. Whilst the strategy proposed in the Pontbren study is considered to bring benefits for 'Tourism', the full afforestation cover that was postulated for the Trent, Severn, Thames study would likely have a negative impact because of the extent of landscape change. The limit between benefit and disbenefit as a result of different percentages of afforestation will depend on catchment specific characteristics, such as size, presence of cultural edifices and social aspects, for example, community attitude and priorities (cf. Rounsevell *et al.* 2010).

Subjectivity in the assessment is another important challenge in an ESS analysis. Different investigators may have different views assigning impacts or prioritising the benefits provided by NFM strategies and identifying the thresholds depending on their level of expertise, area of research and interests. Whilst important research is currently being undertaken in establishing a method for evaluating ESS (Liu *et al.* 2010; Fisher *et al.* 2011; Rutgers *et al.* 2012), a standardised practice is not yet available. For some services it is possible to model changes due to NFM in a similar quantitative framework as is the case for hydrological modelling for flood/flow levels (e.g. carbon sequestration, water quality, crop production), whereas other types of services (notably cultural) necessitate a different approach including the use of qualitative surveys to elicit responses from local stakeholders. The simple scoring method used in this review has its subjective limitations but represents a transparent and equitable approach to assess trade-offs between different types of service, without a bias towards those for which more quantitative data is available. Questions remain however about the most appropriate or comprehensive approaches to evaluate different options and trade-offs in terms of decision making locally and at the catchment scale because of scale and data availability issues (Postchin *et al.* 2008).

The complexity that lies within every category of ESS is different. Whilst the recognition of changes to provisioning service is easily assessed, the losses and indeed gains of regulating and supporting services have a higher level of complexity, with interactions and feedbacks occurring over a range of spatial and temporal scales (Hein *et al.* 2006; Brown *et al.* 2008; Colls *et al.* 2009). Moreover 'Cultural Services' are highly dependent on the local social and environmental context meaning the assessment can only draw tentative conclusions in the absence of detailed information and local surveys.

Comparing between various NFM strategies is very challenging as these measures are aimed to increase water storage, reduce the flood peak or increase the time to peak parameter. In the absence of common indicators that measure their performance, representing them on the same matrix is not possible. More research is needed to develop such indicators and develop a common matrix that will help stakeholders, such as insurance companies, make socially-significant decisions in a transparent and consistent manner (Feld *et al.* 2010).

CONCLUSIONS

A review of recent NFM studies, evaluated in terms of both flood risk reduction and wider ecosystem service benefits, highlighted the importance of geographical setting along with the nature, scale and location of different NFM options. Time lags before the maximum NFM benefits are realised are especially important in those catchments with flood-vulnerable communities for which there is already stakeholder demand for risk reduction, even at current levels of exposure (Harries & Penning-Rowsell 2011). This situation is of course amplified where climate predictions indicate flood risk is likely to increase either directly from altered magnitude-frequency relations of precipitation (hydroclimatic), or indirectly mediated through changes in land management practices.

The study highlights the challenges of mapping ESS and establishing a conceptual framework within which different NFM options can be evaluated because catchments are intrinsically dynamic and complex adaptive ecosystems (cf. Dawson *et al.* 2010). The case-studies reviewed evidenced overwhelmingly net positive benefits, subject to the caveat of unintended consequences (cf. Odoni & Lane 2010).

Whilst fully quantitative and economic valuation of different options remains beyond the scope of this study, the analysis highlights that NFM measure provides at the very least 'low regret' options in relation to climate change adaptation especially in the long term.

The study of ESS is increasingly promoted as a cornerstone of effective environmental management, but there remain many methodological challenges to operationalise the approach and fully integrate options analysis into decision-making at both the policy level and at the local level by catchment managers. A systems-based approach, incorporating alternative land management scenarios, offers a framework to explicitly include flow and flood regulation as one of multiple ESS and thus better situate NFM within the wider context of climate change adaptation in the UK.

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Appendix B

```
$set $mainpath      = C:\MODELING\Tarland\

$set $InitialStateDirectory = $mainpath//output\
$set $DefaultOutputDirectory = $mainpath//output\
$set $inpath_grid    = $mainpath//input\
$set $inpath_meteo   = $mainpath//input\
$set $inpath_hydro   = $mainpath//input\
$set $inpath_ini     = $mainpath//input_ini\
$set $exchngpath     = $mainpath//exchange\

# it is important to set $outpath to an empty string in order to activate
$DefaultOutputDirectory
$set $outpath       =

# readgrids : 1 = read storage grids (as SI, SSNOW,SLIQ...) from hard disk,
0=generate and initialize with 0
$set $readgrids    =  1

# read grids for dynamic phenology -> usually chilling grid should be read in if
availabe because otherwise thermal time method will be applied and not the
sequential model
$set $DPreadgrids   =  0

$set $time          = 60.0
$set $year          = 2006

$set $starthour      = 00
$set $startday       = 01
$set $startmonth     = 01
$set $startyear      = 2004
$set $endhour        = 23
$set $endday         = 31
$set $endmonth       = 12
$set $endyear        = 2006

[model_time]
$starthour         #  start hour
$startday          #  start day
$startmonth        #  start month
$startyear         #  start year
$endhour           #  end hour
$endday            #  end day
$endmonth          #  end month
$endyear           #  end year

$set $grid          =  tarland
$set $stack         =  stack
$set $suffix        =  grd
$set $code          =  s

# variables for standardgrids
# first section: grids, which differ for different subdivisions of the basin
```

```
$set $zone_grid           =  $grid//.zon
$set $subcatchments       =  $grid//.ezg
$set $flow_time_grid      =  $grid//.fzs
$set $river_links_grid    =  $grid//.lnk
$set $regio_grid          =  $grid//.reg

#second section: grids, which doesn't depend on subdivision (only pixel-values are
of interest)
$set $elevation_model     =  $grid//.dhm
$set $RelCellArea_grid    =  $grid//.rca
$set $CellSizeX_grid      =  $grid//.csx
$set $CellSizeY_grid      =  $grid//.csy
$set $slope_grid          =  $grid//.slp
$set $FlowDirection_grid  =  $grid//.fld
$set $aspect_grid         =  $grid//.exp
$set $land_use_grid       =  $grid//.use
$set $ice_firn_grid       =  $grid//.ice
$set $field_capacity_grid =  $grid//.nfk
$set $ATBgrid             =  $grid//.atb
$set $hydr_cond_grid      =  $grid//.k
$set $soil_types          =  $grid//.soil
$set $sky_view_factor_grid =  $grid//.hor
$set $drain_depth_grid    =  $grid//.drn
$set $drain_distance_grid =  $grid//.dis
$set $irrigationcodes     =  $grid//.irr
$set $max_pond_grid       =  $grid//.maxpond
$set $clay_depth_grid     =  $grid//.cly
$set $river_depth_grid    =  $grid//.dep
$set $river_width_grid    =  $grid//.wit
$set $tracer_1            =  $grid//.c1
$set $tracer_2            =  $grid//.c2
$set $tracer_3            =  $grid//.c3
$set $tracer_4            =  $grid//.c4
$set $tracer_5            =  $grid//.c5
$set $tracer_6            =  $grid//.c6
$set $tracer_7            =  $grid//.c7
$set $tracer_8            =  $grid//.c8
$set $tracer_9            =  $grid//.c9
$set $kolmationsgrid      =  $grid//.kol
$set $gw_kx_1_grid        =  $grid//.kx005
$set $gw_kx_2_grid        =  $grid//.kx2
$set $gw_kx_3_grid        =  $grid//.kx3
$set $gw_ky_1_grid        =  $grid//.ky005
$set $gw_ky_2_grid        =  $grid//.ky2
$set $gw_ky_3_grid        =  $grid//.ky3
$set $gw_bound_h_1_grid   =  $grid//.bh1
$set $gw_bound_h_2_grid   =  $grid//.bh2
$set $gw_bound_h_3_grid   =  $grid//.bh3
$set $gw_bound_q_1_grid   =  $grid//.bq1
$set $gw_bound_q_2_grid   =  $grid//.bq2
$set $gw_bound_q_3_grid   =  $grid//.bq3
$set $aquiferthick1       =  $grid//.aq1
$set $aquiferthick2       =  $grid//.aq2
$set $aquiferthick3       =  $grid//.aq3
$set $gw_storage_coeff_1  =  $grid//.s01
$set $gw_storage_coeff_2  =  $grid//.s02
$set $gw_storage_coeff_3  =  $grid//.s03
$set $gw_kolmation_1      =  $grid//.gk1
$set $gw_kolmation_2      =  $grid//.gk2
$set $gw_kolmation_3      =  $grid//.gk3
```

```
$set $lake_grid            = $grid//.lak
$set $taucrit_grid         = $grid//.tau
$set $ThawCoeffPermaFrost  = $grid//.alpha
$set $T_lower_boundary_grid = $grid//.tlowbdry
$set $debris_on_glaciers   = $grid//.debris

# grids for surface hydrology modules
$set $forcingunitsgrid1   = forc1//$grid//.//$suffix
$set $TStartPhenoGrid1    = phen1//$grid//.//$suffix
$set $chillingunitsgrid1  = chill1//$grid//.//$suffix
$set $FStargrid1          = fstar1//$grid//.//$suffix
$set $forcingunitsgrid2   = forc2//$grid//.//$suffix
$set $TStartPhenoGrid2    = phen2//$grid//.//$suffix
$set $chillingunitsgrid2  = chill2//$grid//.//$suffix
$set $FStargrid2          = fstar2//$grid//.//$suffix
$set $forcingunitsgrid3   = forc3//$grid//.//$suffix
$set $TStartPhenoGrid3    = phen3//$grid//.//$suffix
$set $chillingunitsgrid3  = chill3//$grid//.//$suffix
$set $FStargrid3          = fstar3//$grid//.//$suffix
$set $albedo              = albe//$grid//.//$suffix
$set $soilstoragegrid     = sb__//$grid//.//$suffix
$set $throughfall         = qi__//$grid//.//$suffix
$set $snowcover_outflow   = qsno//$grid//.//$suffix
$set $melt_from_snowcover = qsme//$grid//.//$suffix
$set $days_snow           = sday//$grid//.//$suffix
$set $snow_age            = sage//$grid//.//$suffix
$set $snow_rate           = snow//$grid//.//$suffix
$set $rain_rate           = rain//$grid//.//$suffix
$set $firn_melt           = qfir//$grid//.//$suffix
$set $ice_melt            = qice//$grid//.//$suffix
$set $preci_grid          = prec//$grid//.//$suffix
$set $preci_grid1         = prec1//$grid//.//$suffix
$set $preci_grid2         = prec2//$grid//.//$suffix
$set $irrig_grid          = irri//$grid//.//$suffix
$set $etr2etpgrid         = er2ep//$grid//.//$suffix
$set $tempegrid           = temp//$grid//.//$suffix
$set $tempegrid1          = temp1//$grid//.//$suffix
$set $tempegrid2          = temp2//$grid//.//$suffix
$set $windgrid            = wind//$grid//.//$suffix
$set $sunshinegrid        = ssd_//$grid//.//$suffix
$set $radiationgrid       = rad_//$grid//.//$suffix
$set $humiditygrid        = humi//$grid//.//$suffix
$set $vaporgrid           = vapo//$grid//.//$suffix
$set $ETPgrid             = etp_//$grid//.//$suffix
$set $EIPgrid             = eip_//$grid//.//$suffix
$set $ETRgrid             = etr_//$grid//.//$suffix
$set $EVAPgrid            = evap//$grid//.//$suffix
$set $EVARgrid            = evar//$grid//.//$suffix
$set $ETRSgrid            = etrs//$grid//.//$suffix
$set $SSNOgrid            = ssno//$grid//.//$suffix
$set $SLIQgrid            = sliq//$grid//.//$suffix
$set $SSTOgrid            = ssto//$grid//.//$suffix
$set $sat_def_grid        = sd__//$grid//.//$suffix
$set $SUZgrid             = suz_//$grid//.//$suffix
$set $SIFgrid             = sif_//$grid//.//$suffix
$set $EIgrid              = ei__//$grid//.//$suffix
$set $SIgrid              = si__//$grid//.//$suffix
$set $ExpoCorrgrid        = exco//$grid//.//$suffix
$set $Tcorrgrid           = tcor//$grid//.//$suffix
$set $Shapegrid           = shap//$grid//.//$suffix
```

```
$set $INFEXgrid        = infx//$grid//.//$suffix
$set $SATTgrid         = satt//$grid//.//$suffix
$set $Nagrid           = na__//$grid//.//$suffix
$set $SSPgrid          = ssp_//$grid//.//$suffix
$set $Peakgrid         = peak//$grid//.//$suffix
$set $SBiagrid         = sbia//$grid//.//$suffix
$set $fcia_grid        = nfki//$grid//.//$suffix
$set $tavg_grid        = tavg//$grid//.//$suffix

# now variables for unsaturated zone model
$set $SB_1_grid     = sb05//$grid//.//$suffix
$set $SB_2_grid     = sb1_//$grid//.//$suffix
$set $ROOTgrid      = wurz//$grid//.//$suffix
$set $QDgrid        = qd__//$grid//.//$suffix
$set $QIgrid        = qifl//$grid//.//$suffix
$set $GWdepthgrid   = gwst//$grid//.//$suffix
$set $GWthetagrid   = gwth//$grid//.//$suffix
$set $GWNgrid       = gwn_//$grid//.//$suffix
$set $UPRISEgrid    = uprs//$grid//.//$suffix
$set $PERCOLgrid    = perc//$grid//.//$suffix
$set $GWLEVELgrid   = gwlv//$grid//.//$suffix
$set $QDRAINgrid    = qdrn//$grid//.//$suffix
$set $QBgrid        = qb__//$grid//.//$suffix
$set $GWINgrid      = gwin//$grid//.//$suffix
$set $GWEXgrid      = gwex//$grid//.//$suffix
$set $act_pond_grid = pond//$grid//.//$suffix
$set $MACROINFgrid  = macr//$grid//.//$suffix
$set $SUBSTEPSgrid  = step//$grid//.//$suffix

$set $SnowFreeDaysGrid  = sfre//$grid//.//$suffix
$set $SnowCoverDaysGrid = scov//$grid//.//$suffix
$set $ThawDepthGrid     = thdp//$grid//.//$suffix
$set $ThawDepthGridTMod = thaw//$grid//.//$suffix

# variables for groundwater modeling
$set $flowx1grid    = gwx1//$grid//.//$suffix
$set $flowx2grid    = gwx2//$grid//.//$suffix
$set $flowx3grid    = gwx3//$grid//.//$suffix
$set $flowy1grid    = gwy1//$grid//.//$suffix
$set $flowy2grid    = gwy2//$grid//.//$suffix
$set $flowy3grid    = gwy3//$grid//.//$suffix
$set $head1grid     = gwh1//$grid//.//$suffix
$set $head2grid     = gwh2//$grid//.//$suffix
$set $head3grid     = gwh3//$grid//.//$suffix
$set $GWbalance1grid =  gwbalance1//$grid//.//$suffix
$set $GWbalance2grid =  gwbalance2//$grid//.//$suffix
$set $GWbalance3grid =  gwbalance3//$grid//.//$suffix

# result grids for surface routing model
$set $surfspeed_grid     = sfcv//$grid//.//$suffix
$set $surfflux_grid      = sflx//$grid//.//$suffix
# some new stacks and grids for the dynamic glacier model
$set $firn_WE_stack          = glfirn//$stack//.//$suffix
$set $GlacierMassBalance     = glmb//grid//.//$suffix
$set $OldGlacierMassBalance  = glmb_old//grid//.//$suffix
$set $glacierizedCells_grid  = glc_//$grid//.//$suffix
$set $glacier_codes_grid     = glid//$grid//.//$suffix

# result-stacks for Unsatzonmodel
$set $Thetastack             = teth//$stack//.//$suffix
```

```
$set $hydraulic_heads_stack   = hhyd//$stack//.//$suffix
$set $geodetic_altitude_stack = hgeo//$stack//.//$suffix
$set $flowstack              = qu__//$stack//.//$suffix
$set $concstack              = conc//$stack//.//$suffix
# result-stacks for temperatures in Unsatzonmodel
$set $Temperaturestack       = tsoil//stack//.//$suffix

# explanation of writegrid and outputcode some lines below
$set $Writegrid     =  3
$set $Writestack    =  3

$set $once_per_interval  =  2001
$set $avrg_per_24Invs    =  2024
$set $sum_per_24Invs     =  4024
$set $routing_code       =  4001

[output_list]
0          # number of subbasins which are scheduled for output (is only of interest, if the code for the statistic files are >5000)
0

[output_interval]
1          # increment of time steps until an output to the screen is done (24 = each day one output, if time steo = 1h)
0          # warning level for interpolation (no station within search radius)
1          # unit of routed discharge (0=mm/timestep, 1=m3/s)
0          # minutes from the hour-entry in the input data files until the end
# of the time step is reached 0 if the end of time step is given like "84 01 01 01",
# but it should be $time if the begin is given like in "84 01 01 00"

WriteAsciiGrids = 1                                  # 0 if grids should be written in WaSiM native format, 1 if in ESRI ASCII format
InitialStateDirectory = $InitialStateDirectory       # if using this parameter, all state grids  as well as the storage_richards.ftz file will be expected in that directory for reading
DefaultOutputDirectory = $DefaultOutputDirectory   # this is the default output directory, all output is written to unless the given filename contains an absolute path (starting with either / or ~ for UNIX or a drive letter and :\ for Windows

[coordinates]
57.1243        # geogr. latitude (center of the basin -> for radiation calculations)
-2.84574       # geogr. longitude (center of the basin)
0          # meridian according to the official time (middle europe: 15)(east: 0 ... +180 degree, west: 0 ... -180 (or 360 ... 180)
0          # time shift of Meteo-data-time with respect to the true local time (mean sun time)

[region_transition_distance]
77000 # in m

[soil_surface_groundwater_substeps].
1                      # number of sub time steps for the module group surface routing, unsaturated zone model and groundwater model (and accumulation of real evapotranspiration)
# Values to start with are 1 (default), 2 (half of the common time step), 3 etc.

[elevation_model]
$inpath_grid//$elevation_model    # grid with the digital elevation data

[zone_grid]
```

```
$inpath_grid//$zone_grid        # grid with Zone codes

$set $lai_grid      = lai_//$grid//.//$suffix
$set $z0_grid       = z0_//$grid//.//$suffix
$set $root_grid     = root_//$grid//.//$suffix
$set $rse_grid      = rse_//$grid//.//$suffix
$set $rsi_grid      = rsi_//$grid//.//$suffix
$set $rsc_grid      = rsc_//$grid//.//$suffix
$set $albedo_grid           = albedo_//$grid//.//$suffix
$set $vcf_grid      = vcf_//$grid//.//$suffix

$set $lai_stat      = lai_//$grid//.//$code//$year
$set $z0_stat       = z0_//$grid//.//$code//$year
$set $root_stat     = root_//$grid//.//$code//$year
$set $rse_stat      = rse_//$grid//.//$code//$year
$set $rsi_stat      = rsi_//$grid//.//$code//$year
$set $rsc_stat      = rsc_//$grid//.//$code//$year
$set $albedo_stat           = albedo_//$grid//.//$code//$year
$set $vcf_stat      = vcf_//$grid//.//$code//$year

[standard_grids]
20                              # number of standard grids
$inpath_grid//$regio_grid               regression_regions          1   # region
grid if using multiple regression perameter files for meteorological data
interpolation
$inpath_grid//$slope_grid               slope_angle                         1
# grid with slope angle data
$inpath_grid//$aspect_grid                      slope_aspect                1
# grid with slope aspect data
$inpath_grid//$subcatchments                    zonegrid_soilmodel          1   # zone
grid for the runoff generation model (and unsaturated zone model)
$inpath_grid//$land_use_grid                    landuse
        fillcode = 1 # writecode = 8 readcode = 1 outname =
$outpath//$land_use_grid                # grid with land use data (will be written out
after reading in for getting gthe filles values)
$inpath_grid//$soil_types                       soil_types
        fillcode = 1 # writecode = 8 readcode = 1 outname =
$outpath//$soil_types       # soil types as codes for the soil table
$inpath_grid//$flow_time_grid                   flow_times
        fillcode = 1 # writecode = 8 readcode = 1 outname =
$outpath//$flow_time_grid               # grid with flow times for surface runoff to the
subbasin outlet
$inpath_grid//$river_depth_grid                 river_depth                         1
# grid with the depth of all streams in the stream network in m
$inpath_grid//$river_width_grid                 river_width                         1
# grid with the witdh of all streams in m
$inpath_grid//$river_links_grid                 river_links                         0
# grid with codes of tributaries, from which a channel was routed (only for real
routing channels!!!)
$inpath_grid//$kolmationsgrid                   kolmation                           1
# grid with codes of tributaries, from which a channel was routed (only for real
routing channels!!!)
$inpath_grid//$aquiferthick1                    aquifer_thickness_1         fillcode = 1
# writecode = 8 readcode = 1 outname = $outpath//$aquiferthick1       # grid with
thickness of first aquifer (m from soil surface to the aquifer bottom)
$inpath_grid//$gw_storage_coeff_1               gw_storage_coeff_1          fillcode = 1
# writecode = 8 readcode = 1 outname = $outpath//$gw_storage_coeff_1          #
storage coefficients for 1. aquifer
```

$inpath_grid//$gw_bound_h_1_grid gw_boundary_fix_h_1 0 # periodicity = 1 D 12 persistent = 0 # boundary conditions 1 constant head for layer 1
$inpath_grid//$gw_bound_q_1_grid gw_boundary_fix_q_1 0 # boundary conditions 2 (given flux perpendicular to the border) for layer 1
$inpath_grid//$gw_kx_1_grid gw_k_x_1
fillcode = 1 # writecode = 8 readcode = 1 outname = $outpath//$gw_kx_1_grid # lateral hydraulic conductivities for the 1. aquifer in x direction
$inpath_grid//$gw_ky_1_grid gw_k_y_1
fillcode = 1 # writecode = 8 readcode = 1 outname = $outpath//$gw_ky_1_grid # lateral hydraulic conductivities for the 1. aquifer in y direction
$inpath_grid//$gw_kolmation_1 gw_kolmation_1 1 # kolmation (leakage factor) between 1st and 2nd aquifer
$inpath_grid//$drain_depth_grid drainage_depth 1 # grid with depth of drainage pipes in the soil
$inpath_grid//$drain_distance_grid drainage_distance 1 # grid with distances of the drainage pipes or hoses from each other

variable grids are used by more than one module or can be changed (like albedo and soil storage)
$set $SurfStorSiltingUp = sfstsu//$grid//.//$suffix
$set $pondgridtopmodel = pond_top//$grid//.//$suffix
$set $VegetationStart = vegstart//$grid//.//$suffix
$set $VegetationStop = vegstop//$grid//.//$suffix
$set $VegetationDuration = vegduration//$grid//.//$suffix

[variable_grids]
2 # Number of variable grids to read
$outpath//$albedo albedo 1 0 # albedo; for time without snow derived from land use data
$Writegrid # Writegrid for $albedo
$readgrids # 0. if albedo is derived from land use at model start time. 1. if albedo is read from file
$outpath//$soilstoragegrid soil_storage 1 0 # soil water storage
$Writegrid # Writegrid for this grid
$readgrids # 0. if soil_storage should be derived from soil types. 1. if it should be read from file

parameters for interpolation of meteorological input data
$set $SzenUse = 0
$set $IDWmaxdist = 20000
$set $IDWweight = 2
$set $Anisoslope = 0.0
$set $Anisotropie = 1.0

explanation of writegrid and outputcode some lines below
$set $Writegrid = 3
$set $Writestack = 3

[meteo_data_count]
5

[meteo_names]
the name of the temperature interpolation result is mandatory if dynamic phenology is used (calculating forcing units depends on a grid called "temperature")
temperature
#temperature_reg2

precipitation
#precipitation_reg2
wind_speed
air_humidity
#vapor_pressure
#global_radiation
sunshine_duration

[temperature]
4 # methods, see comments above
$inpath_meteo//temp.txt AdditionalColumns=0 # file name with station data (if method = 1, 3 or 4, else ignored)
#$inpath_meteo//t2m_reg1_//$year//.out # file name with regression data (if method = 2 or 3)
820 1400 200 1 300 # lower inversion [m asl], upper inversion [m asl], tolerance [m], overlap [0/1 for true/false], clusterlimit [m] $outpath//$tempegrid1
name of the output grid (is also used for deriving names of daily, monthly, yearly sums or averages)
$outpath//$tempegrid1 # name of the output grid (is also used for deriving names of daily, monthly, yearly sums or averages)
5//$Writegrid # 0, if no grid-output is needed, else one of the codes described above
1.0 # correction faktor for results
$outpath//t2m_reg1_//$grid//.//$code//$year $once_per_interval # file name for the statistic output (statially averaged values per time step and subcatchment...)
9998 # error value: all data in the input file greater than this values or lesser the negative value are nodata
$IDWweight # weighting of the reciprocal distance for IDW
0.2 # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist # max. distance of stations to the actual interpolation cell
-65 # slope of the mean axis of the anisotropy-ellipsis (-90 ... +90 degree, mathem. positive)
0.8 # ratio of the short to the long axis of the anisotropy-ellipsis
-40 # lower limit of interpolation results
-40 # replace value for results below the lower limit
40 # upper limit for interpolation results
40 # replace value for results with larger values than the upper limit
$SzenUse # 1=use scenario data for correction, 0=dont use scenarios
1 # 1=add scenarios, 2=multiply scenarios, 3=percentual change
4 # number of scenario cells

[precipitation]
4 # method: 1=idw 2=regress 3=idw+regress 4=thiessen 5=bilinear 6=bilinear gradients and residuals linarly combined, 7=bicubic spline, 8=bicubic splines of gradients and residuals linearly combined, 9=read grids according to the name in a grid list file, 10=regression from Stationdata, 11=regression and IDW from station data

$inpath_meteo//precip.txt AdditionalColumns=0 # file name with station data (if method = 1,3,4,5,6,7,8 or 9 else ignored)
820 1400 200 1 300 # lower inversion [m asl], upper inversion [m asl], tolerance [m], overlap [0/1 for true/false], clusterlimit [m]
$outpath//$preci_grid1 # name of the output grid (is also used for deriving names of daily, monthly, yearly sums or averages)
1//$Writegrid # 0, if no grid-output is needed, else one of the codes described above
1 # correction faktor for results
$outpath//prec_reg1_//$grid//.//$code//$year $once_per_interval # file name for the statistic output (statially averaged values per time step and subcatchment...)
9998 # error value: all data in the input file greater than this values or lesser the negative value are nodata
$IDWweight # weighting of the reciprocal distance for IDW
0.75 # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist # max. distance of stations to the actual interpolation cell
$Anisoslope # slope of the mean axis of the anisotropy-ellipsis (-90 ... +90 degree, mathem. positive)
$Anisotropie # ratio of the short to the long axis of the anisotropy-ellipsis
0.1 # lower limit of interpolation results
0 # replace value for results below the lower limit
900 # upper limit for interpolation results
900 # replace value for results with larger values than the upper limit
$SzenUse # 1=use scenario data for correction, 0=dont use scenarios
2 # 3 # 1=add scenarios, 2=multiply scenarios, 3=percentual change
1 # 4 # number of scenario cells

[wind_speed]
4 # method: 1=idw 2=regress 3=idw+regress 4=thiessen 5=bilinear 6=bilinear gradients and residuals linarly combined, 7=bicubic spline, 8=bicubic splines of gradients and residuals linearly combined, 9=read grids according to the name in a grid list file, 10=regression from Stationdata, 11=regression and IDW from station data
$inpath_meteo//wind.txt AdditionalColumns=0 # file name with station data (if method = 1, 3 or 4, else ignored)
$inpath_meteo//wind__//$year//.out # file name with regression data (if method = 2 or 3)
$outpath//$windgrid # name of the output grid (is also used for deriving names of daily, monthly, yearly sums or averages)
$Writegrid # 0, if no grid-output is needed, else one of the codes described above
1 # correction faktor for results
$outpath//wind//$grid//.//$code//$year $once_per_interval # file name for the statistic output (statially averaged values per time step and subcatchment...)
9998 # error value: all data in the input file greater than this values or lesser the negative value are nodata
$IDWweight # weighting of the reciprocal distance for IDW
0.3 # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist # max. distance of stations to the actual interpolation cell
$Anisoslope # slope of the mean axis of the anisotropy-ellipsis (-90 ... +90 degree, mathem. positive)
$Anisotropie # ratio of the short to the long axis of the anisotropy-ellipsis
0 # lower limit of interpolation results
0 # replace value for results below the lower limit
90 # upper limit for interpolation results
90 # replace value for results with larger values than the upper limit
$SzenUse # 1=use scenario data for correction, 0=dont use scenarios

3 # 1=add scenarios, 2=multiply scenarios, 3=percentual change
4 # number of scenario cells

[sunshine_duration]
4 # method: 1=idw 2=regress 3=idw+regress 4=thiessen 5=bilinear 6=bilinear gradients and residuals linarly combined
$inpath_meteo//sunshine.txt AdditionalColumns=0 # file name with station data (if method = 1, 3 or 4, else ignored)
$inpath_meteo//ssd___//$year//.out # file name with regression data (if method = 2 or 3)
$outpath//$sunshinegrid # name of the output grid (is also used for deriving names of daily, monthly, yearly sums or averages)
$Writegrid # 0, if no grid-output is needed, else one of the codes described above
1.0 # correction faktor for results
$outpath//ssd_//$grid//.//$code//$year $once_per_interval # file name for the statistic output (statially averaged values per time step and subcatchment...)
9998 # error value: all data in the input file greater than this values or lesser the negative value are nodata
$IDWweight # weighting of the reciprocal distance for IDW
0.5 # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist # max. distance of stations to the actual interpolation cell
$Anisoslope # slope of the mean axis of the anisotropy-ellipsis (-90 ... +90 degree, mathem. positive)
$Anisotropie # ratio of the short to the long axis of the anisotropy-ellipsis
0 # lower limit of interpolation results
0 # replace value for results below the lower limit
1.0 # upper limit for interpolation results
1.0 # replace value for results with larger values than the upper limit
$SzenUse # 1=use scenario data for correction, 0=dont use scenarios
3 # 1=add scenarios, 2=multiply scenarios, 3=percentual change
1 # number of scenario cells

[air_humidity]
4 # method: 1=idw 2=regress 3=idw+regress 4=thiessen 5=bilinear 6=bilinear gradients and residuals linarly combined
$inpath_meteo//humid.txt AdditionalColumns=0 # file name with station data (if method = 1, 3 or 4, else ignored)
820 1400 200 1 300 # lower inversion [m asl], upper inversion [m asl], tolerance [m], overlap [0/1 for true/false], clusterlimit [m]
$outpath//$humiditygrid # name of the output grid (is also used for deriving names of daily, monthly, yearly sums or averages)
$Writegrid # 0, if no grid-output is needed, else one of the codes described above
0.01 # correction faktor for results
$outpath//humi//$grid//.//$code//$year $once_per_interval # file name for the statistic output (statially averaged values per time step and subcatchment...)
9998 # error value: all data in the input file greater than this values or lesser the negative value are nodata
$IDWweight # weighting of the reciprocal distance for IDW
0.5 # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist # max. distance of stations to the actual interpolation cell
$Anisoslope # slope of the mean axis of the anisotropy-ellipsis (-90 ... +90 degree, mathem. positive)
$Anisotropie # ratio of the short to the long axis of the anisotropy-ellipsis
0.01 # lower limit of interpolation results
0.01 # replace value for results below the lower limit
1.0 # upper limit for interpolation results

```
1.0                    # replace value for results with larger values than the upper limit
$SzenUse               # 1=use scenario data for correction, 0=dont use scenarios
3                      # 1=add scenarios, 2=multiply scenarios, 3=percentual change
1                      # number of scenario cells

[RegionalSuperposition]
0
$time
NumberOfEntities = 2;
temperature {
        entityinputgrid = temperature_reg1 ;
                regions = 1   2   ;
                weights = 1.0 0.0 ;
        entityinputgrid = temperature_reg2 ;
                regions = 1   2   ;
                weights = 0.0 1.0 ;
        outputgrid  = $outpath//$tempegrid ;
                writecode = 5//$Writegrid ;
        outputtable = $outpath//t2m_//$grid//.//$code//$year;
                statcode  = $once_per_interval;
}
precipitation {
        entityinputgrid = precipitation_reg1 ;
                regions = 1   2   ;
                weights = 1.0 0.0 ;
        entityinputgrid = precipitation_reg2 ;
                regions = 1   2   ;
                weights = 0.0 1.0 ;
        outputgrid  = $outpath//$preci_grid ;
                writecode = 1//$Writegrid ;
        outputtable = $outpath//prec//$grid//.//$code//$year;
                statcode  = $once_per_interval;
}

[precipitation_correction]
1             # 0=ignore this module, 1 = run the module
.458          # Snow-rain-temperature
.702          # liquid:   b in:  y = p(ax + b)
.049          # liquid:   a in:  y = p(ax + b) = 1% more per m/s + 0.5% constant
0.93          # Snow:     b in:  y = p(ax + b)
.05           # Snow:     a in:  y = p(ax + b) = 15% more per m/s + 45% constant

[radiation_correction]
1             # 0=ignore this module, 1 = run the module
$time         # duration of a time step in minutes
2             # control parameter for radiation correction (see above)
$outpath//$Tcorrgrid # name of the grids with the corrected temperatures
$Writegrid    # Writegrid for corrected temperatures
5             # factor x for temperature correction x * (-1.6 .... +1.6)
$outpath//$ExpoCorrgrid   # name of the grids with the correction factors for the direct radiation
$Writegrid    # Writegrid
$outpath//$Shapegrid # name of the grids for codes 1 for theor. shadow, 0 for theor. no shadow (day; assumed: SSD=1.0)
$Writegrid    # Writegrid
1             # interval counter, after reaching this value, a new correction is calculated (3=all 3 hours a.s.o.)
1             # Splitting of the interval, usefull for time step=24 hours (then: split=24, -> each hour one correction calculation)
```

[evapotranspiration]
1 # 0=ignore this module, 1 = run the module
$time # duration of a time step in minutes
1 # Method: 1=Penman-Monteith, 2=Hamon (only daily), 3=Wendling (only daily) 4= Haude (only daily)
0.2 0.2 0.35 0.4 0.4 0.4 0.4 0.4 0.35 0.2 0.2 0.2 # PEC correction factor for HAMON-evapotranspiration
0.20 0.20 0.21 0.29 0.29 0.28 0.26 0.25 0.22 0.22 0.20 0.20 # fh (only for method 4: Haude) monthly values (Jan ... Dec) (here: for Grass)
0.5 # fk -> factor for Wendling-evapotranspiration (only for Method = 3)
$outpath//$ETPgrid # result grid for pot. evapotranspiration in mm/dt
1//$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//etp_//$grid//.//$code//$year $once_per_interval # statisticfile for Teilgebiete of pot. evapo-Transpiration
$outpath//$ETRgrid # result grid for real evapotranspiration in mm/dt
1//$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//etr_//$grid//.//$code//$year $once_per_interval # statistic for subcatchments (zones) of the real evapotranspiration
$outpath//$EVAPgrid # result grid for real evapotranspiration in mm/dt
1//$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//evap//$grid//.//$code//$year $once_per_interval # statistic for subcatchments (zones) of the potential evaporation
$outpath//$EVARgrid # result grid for real evapotranspiration in mm/dt
1//$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//evar//$grid//.//$code//$year $once_per_interval # statistic for subcatchments (zones) of the real evaporation
$outpath//$ETRSgrid # result grid for real snow evapotranspiration in mm/dt
1//$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//etrs//$grid//.//$code//$year $once_per_interval # statistic for subcatchments (zones) of the real snow evaporation
$outpath//$EIPgrid # result grid for pot. interception evaporation in mm/dt
1//$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//eip_//$grid//.//$code//$year $once_per_interval # statisticfile for zones of pot. interception evaporation
$outpath//rgex//$grid//.//$code//$year $once_per_interval # statistic for subcatchments (zones) of the corrected radiation
+0.23 +1.77 -2.28 +1.28 # coefficients c for Polynom of order 3 RG = c1 + c2*SSD + c3*SSD^2 + c4*SSD^3
+0.072 -0.808 +2.112 -0.239 # coefficients x for Polynom of order 3 SSD = x1 + x2*RG + x3*RG^2 + x4*RG^3
0.88 0.05 # Extinktion coefficient for RG-modeling (Phi and dPhi) (summer phi = phi-dphi, winter phi=phi+dphi)
1654.0 # recession constant (e-function for recession of the daily temperature amplitude with altitude [m]
3.3 4.4 6.1 7.9 9.4 10.0 9.9 9.0 7.8 6.0 4.2 3.2 # monthly values of the max. daily T-amplitudes (for 0 m.a.s.l)
0.62 0.1 # part of the temperature amplitude (dt), that is added to the mean day-temperature
(followed by the range of changing within a year ddt) to get the mean temperature of light day
in the night: mean night temperature is mean day temperature minus (1-dt)*(temp. amplitude)

```
[snow_model]
1              # 0=ignore this module, 1 = run the module
$time             # duration of a time step in minutes
1              # method 1=T-index, 2=t-u-index, 3=Anderson comb., 4=extended
com.
1.0             # transient zone for rain-snow (T0R +- this range)
2.431              # T0R    temperature limit for rain (Grad Celsius)
.458             # T0     temperature limit snow melt
0.1             # CWH    storage capacity of the snow for water (relative part)
1.0             # CRFR   coefficient for refreezing
2.34             # C0     degree-day-factor mm/d/C
0.8             # C1     degree-day-factor without wind consideration  mm/(d*C)
0.17             # C2     degree-day-factor considering wind mm/(d*C*m/s)
0.07             # z0     roughness length cm for energy bilance methods (not used)
1.0             # RMFMIN minimum radiation melt factor      mm/d/C comb. method
2.5             # RMFMAX maximum radiation melt factor      mm/d/C comb. method
0.45             # Albedo for snow (Min)
0.90             # Albedo for snow (Max)
$outpath//$rain_rate       # rain rate
1//$Writegrid            # 0, if no grid-output is needed, else one of the codes
described above
$outpath//rain//$grid//.//$code//$year $once_per_interval # rain rate
$outpath//$snow_rate       # snow rate
1//$Writegrid            # 0, if no grid-output is needed, else one of the codes
described above
$outpath//snow//$grid//.//$code//$year $once_per_interval # snow rate
$outpath//$days_snow       # days with snow (SWE > 5mm)
$Writegrid              # 0, if no grid-output is needed, else one of the codes
described above
$outpath//sday//$grid//.//$code//$year $once_per_interval # days with snow
(SWE > 5mm)
$outpath//$snow_age        # snow age (days without new snow)
$Writegrid              # 0, if no grid-output is needed, else one of the codes
described above
$outpath//sage//$grid//.//$code//$year $once_per_interval # days since last
snowfall
$outpath//albe//$grid//.//$code//$year $once_per_interval # Albedo
$outpath//$snowcover_outflow # discharge from snow, input (precipitation) for
following modules
$Writegrid              # 0, if no grid-output is needed, else one of the codes
described above
$outpath//qsch//$grid//.//$code//$year $once_per_interval # melt flow (or rain, if
there is no snow cover) in mm/dt
$outpath//$melt_from_snowcover # discharge from snow, input (precipitation) for
following modules
$Writegrid              # 0, if no grid-output is needed, else one of the codes
described above
$outpath//qsme//$grid//.//$code//$year $once_per_interval # melt flow in
mm/dt
$outpath//$SSNOgrid        # name of the grids with the snow storage solid in mm
$Writegrid              # 0, if no grid-output is needed, else one of the codes
described above
$outpath//$SLIQgrid        # name of the grids with the snow storage liquid in mm
$Writegrid              # 0, if no grid-output is needed, else one of the codes
described above
$outpath//ssto//$grid//.//$code//$year $once_per_interval # total snow storage,
in mm, (liquid and solid fraction)
$outpath//$SSTOgrid        # name of the grids with the total snow storage solid
AND liquid in mm
```

$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$readgrids # 1=read snow storage solid, liquid grids from disk, 0=generate new grids

[ice_firn]
0

[permafrost]
0

[interception_model]
1 # 0=ignore this module, 1 = run the module
$time # duration of a time step in minutes
1 # method: 1 = use ETP for calculating EI; 2 = use EIP for calculating EI (only effective for method 1 in evapotranspiration model -> for other methods, ETP = EIP)
$outpath//$throughfall # result grid : = outflow from the interception storage
$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//qi__//$grid//.//$code//$year $once_per_interval # statistic file interception storage outflow
$outpath//$EIgrid # Interzeption evaporation, grid
1//$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//ei__//$grid//.//$code//$year $once_per_interval # zonal statistic
$outpath//$SIgrid # storage content of the interception storage
1//$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//si__//$grid//.//$code//$year $once_per_interval # zonal statistic For interception storage content
0.35 # layer thickness of the waters on the leaves (multiplied with LAI -> storage capacity)
$readgrids # 1=read grids from disk, else generate internal

[infiltration_model]
1 # 0=ignore this module, 1 = run the module
$time # duration of a time step in minutes
$outpath//$INFEXgrid # grid with infiltration excess in mm (surface runoff)
$Writegrid # Writegrid for surface discharge (fraction 1)
$outpath//infx//$grid//.//$code//$year $once_per_interval # statistic file for the infiltration excess
$outpath//$SATTgrid # grid with code 1=saturation at interval start, 0 =no saturation.
$Writegrid # Writegrid for saturation code grids
0.1 # fraction of reinfitrating water (of the infiltration excess)

$set $SDISPgrid = sdis//$grid//.//$suffix
$set $RPAUSgrid = paus//$grid//.//$suffix
$set $EKIN_grid = ekin//$grid//.//$suffix
$set $TSBB_grid = tsbb//$grid//.//$suffix
$set $QDSU_grid = qdsu//$grid//.//$suffix

[SiltingUpModel]
0 # 0=ignore this module, 1 = run the module

[SurfaceRoutingModel]
0 # 0=ignore this module, 1 = run the module

[lake_model]
0 # 0=ignore this module, 1 = run the module

[unsatzon_model]
1 # 0=ignore this module, 1 = run the module
$time # duration of a time step in minutes
3 # method, 1=simple method (will not work anymore from version 7.x), 2 = FDM-Method 3 = FDM-Method with dynamic time step down to 1 secound
1 # controlling interaction with surface water: 0 = no interaction, 1 = exfiltration possible 2 = infiltration and exfiltration possible
0 # controlling surface storage in ponds: 0 = no ponds, 1 = using ponds for surface storage (pond depth as standard grid needed -> height of dams oround fields)
1 # controlling artificial drainage: 0 = no artificial drainage 1 = using drainage (drainage depth and horizontal pipe distances as standard grids needed!)
0 # controlling clay layer: 0 = no clay layer, 1 = assuming a clay layer in a depth, specified within a clay-grid (declared as a standard grid)
5e-8 # permeability of the clay layer (is used for the clay layer only)
4 # parameter for the initialization of the gw_level (range between 1..levels (standard: 4))
$outpath//qdra//$grid//.//$code//$year $once_per_interval # results drainage discharge in mm per zone
$outpath//gwst//$grid//.//$code//$year $once_per_interval # results groundwater depth
$outpath//gwn_//$grid//.//$code//$year $once_per_interval # results mean groundwater recharge per zone
$outpath//sb05//$grid//.//$code//$year $once_per_interval # results rel. soil moisture within the root zone per zone
$outpath//sb1_//$grid//.//$code//$year $once_per_interval # results rel. soil moisture within the unsat. zone (0m..GW table) per zone
$outpath//wurz//$grid//.//$code//$year $once_per_interval # results statistic of the root depth per zone
$outpath//infx//$grid//.//$code//$year $once_per_interval # results statistic of the infiltration excess
$outpath//pond//$grid//.//$code//$year $once_per_interval # results statistic of the ponding water storage content
$outpath//qdir//$grid//.//$code//$year $once_per_interval # results statistic of the direct discharge
$outpath//qifl//$grid//.//$code//$year $once_per_interval # results statistic of the interflow
$outpath//qbas//$grid//.//$code//$year $once_per_interval # results statistic of the baseflow
$outpath//qges//$grid//.//$code//$year $once_per_interval # results statistic of the total discharge
$outpath//gwin//$grid//.//$code//$year $once_per_interval # statistic of the infiltration from surface water into groundwater (from rivers and lakes)
$outpath//gwex//$grid//.//$code//$year $once_per_interval # statistic of the exfiltration from groundwater into surface water (into rivers and lakes)
$outpath//macr//$grid//.//$code//$year $once_per_interval # statistic of infiltration into macropores
$outpath//qinf//$grid//.//$code//$year $once_per_interval # statistic of total infiltration into the first soil layer
$outpath//$SB_1_grid # grid with actual soil water content for the root zone
$Writegrid # Writecode for this grid
$outpath//$SB_2_grid # grid with actual soil water content for the entire unsaturated zone

```
$Writegrid                                            # Writecode for this grid
$outpath//$ROOTgrid                  # grid with root depth
$Writegrid                   # Writecode for this grid
$outpath//$Thetastack                # stack, actual soil water content for all soil levels
$Writegrid                                            # Writecode for this stack
$outpath//$hydraulic_heads_stack     # stack, contaiing hydraulic heads
$Writestack                  # Writecode for this stack
$outpath//$geodetic_altitude_stack   # stack, containig geodaetic altitudes of the soil levels (lower boudaries)
$Writestack                  # Writecode for this stack
$outpath//$flowstack                 # stack, containing the outflows from the soil levels
$Writestack                  # Writecode for this stack
$outpath//$GWdepthgrid               # grid with groudwaterdepth
$Writegrid                                            # Writecode for this grid
$outpath//$GWthetagrid               # grid with theta in GWLEVEL
$Writegrid                   # Writecode for this grid
$outpath//$GWNgrid                   # grid with groundwater recharge
$Writegrid                                            # Writecode for this grid
$outpath//$GWLEVELgrid               # grid with level index of groundwater surface (Index der Schicht)
$Writegrid                   # Writecode for this grid
$outpath//$QDRAINgrid                # grid with the drainage flows
$Writegrid                   # Writecode for this grid
$outpath//$SATTgrid                  # grid with code 1=saturation at interval start, 0 no sat.
$Writegrid                   # Writecode for this grid
$outpath//$INFEXgrid                 # grid with infiltration excess in mm (surface discharge)
$Writegrid                   # Writecode for this grid
$outpath//$QDgrid            # grid with direct discharge
1//$Writegrid          # Writecode for this grid
$outpath//$QIgrid            # grid with Interflow
1//$Writegrid          # Writecode for this grid
$outpath//$QBgrid            # grid with baseflow
1//$Writegrid                                         # Writecode for this grid
$outpath//$GWINgrid                  # grid with infiltration from rivers into the soil (groundwater)
1//$Writegrid          # Writecode for this grid
$outpath//$GWEXgrid                  # grid with exfiltration (baseflow) from groundwater (is only generated, if groundwater module is active, else baseflow is in QBgrid)
1//$Writegrid          # Writecode for this grid
$outpath//$act_pond_grid             # grid with content of ponding storge
$Writegrid                   # Writecode for this grid
$outpath//$UPRISEgrid                # grid with amount of capillary uprise (mm)
1//$Writegrid          # Writecode for this grid
$outpath//$PERCOLgrid                # grid with amount of percolation (mm)
1//$Writegrid          # writegrid for this grid
$outpath//$MACROINFgrid              # grid with amount of infiltration into macropores (mm)
```

1//$Writegrid # Writecode for this grid
$outpath//$irrig_grid # grid with irrigation amount (will be written when irrigation is used, only)
$Writegrid # writegrid for this grid (however: will be written when irrigation is used, only)
150 150 # coordinates of control plot, all theta and qu-values are written to files (qu.dat, theta.dat in the directory, from which the model is started)
$outpath//qbot//$grid//.//$code//$year # name of a file containing the flows between the layers of the control point
$outpath//thet//$grid//.//$code//$year # name of a file containing the soil moisture as theta values of the layers of the control point
$outpath//hhyd//$grid//.//$code//$year # name of a file containing the hydraulic head of the layers of the control point
$outpath//otherdata//$grid//.//$code//$year # name of a file containing some other water balance data of the control point (non layer data)
$outpath//etrd//$grid//.//$code//$year # name of a file containing the withdrawal of soil water for each layer for the control point (due to transpiration)
$outpath//intd//$grid//.//$code//$year # name of a file containing the interflow for the soil layers of the control point
11 22 33 # codes of the subbasins (in the subbasin grid)
12.0 12.0 12.0 # recession parameters QD (h)
36.0 36.0 36.0 # recession parameters QI (h)
1.00 1.00 1.00 # flow density (for Interflow, channels per km)
.04 .04 .04 # recession parameters k for Base discharge (in QB = Q0*exp(-k/z)) with z = depth to groundwater
.638 .638 .638 # correction of transmissivities Q0 for Baseflow in QB = Q0 * exp(-k/z)
.1239 .1239 .1239 # fraction of snow melt, which is direct flow (no infiltration)
$readgrids # meanings are extended now! read the follwing comments
$outpath//storage_richards.ftz # if readgrids = 1, then this file contains the contents of the flow travel time zones for interflow and surface flow and for the tracers
100 # minimum dynamic time step in secounds. the smaller this number, the longer the model runs but the results will be more accurate due to a maintained Courant condition
$outpath//step//$grid//.//$code//$year $once_per_interval # results statistic of the number of substeps
$outpath//$SUBSTEPSgrid # grid with number of substeps --> a good idea is to use writecode 5x (e.g. 53) to get the average number of substeps per cell for the model run
5//$Writegrid # for substeps, the areal distribution is of interest for the annual average value. This is code 6 as first digit in 2-digit codes. Or use 5 for the entire model run

the following section for heat transfer can be used with WaSiM version 9.0 ff
[heat_transfer]
0

[ExternalCoupling]
0 # 0 = no coupling, 1=coupling

[irrigation]
0 # 0=ignore this module, 1 = run the module

[groundwater_flow]
1 # 0=ignore the module, 1 = run the module
$time # duration of a time step in minutes; doen't change the value unless you have strong reasons to do so!!
1 # solving method: 1=Gauss-Seidel-iteration (using alpha for control wether it is explicite, partly or fully implicite), 2=PCG (not yet implemented
1000 # if iterative solving method (1): max.numberof iterations
0.0001 # if iterative solving method (1): max. changes between two iterations
0.0 # Alpha for estimation of central differences 0.5 = Crank-Nicholson Method, 0 = fully explicite, 1 = fully implicite
-1.20 # factor for relaxing the iteration if using iterativemethod (successive over[/under] relaxation)
$readgrids # 1=read grids for heads from disk, 0=do not read but initialize with gw-level from unsaturated zone
1 # number of layers
50 50 # coordinates of a control point for all fluxes and for each layer : q0..q4, leakage up and down
$outpath//glog//$grid//.//$code//$startyear # name of a file containing the flows between of the control point
0 # use Pond Grid -> this enables the model to use the hydraulic head of a pond in addition to the groundwater itself 0=use traditional method without pond (default), 1=use ponds
$outpath//$head1grid # (new) grid for hydraulic heads for layer 1
$Writegrid # writecode for hydraulic heads for layer 1
$outpath//$flowx1grid # (new) grid for fluxes in x direction for layer 1
$Writegrid # writecode for flux-x-grid in layer 1
$outpath//$flowy1grid # (new) grid for fluxes in y direction for layer 1
$Writegrid # writecode for flux-y-grid in layer 1
$outpath//$GWbalance1grid # (new) grid for balance (difference of storage change vs. balance of fluxes -> should be 0 or the amount of in-/outflows by boundary conditions
$Writegrid # writecode for balance control grid in layer 1 (should be at least one sum grid per year --> Code = 20 or 23 (if old grids must be read in)
13 # writecode for balance control grid in layer 2 (should be at least one sum grid per year --> Code = 20 or 23 (if old grids must be read in)
$outpath//$head3grid # (new) grid for hydraulic heads for layer 3
$Writegrid # writecode for hydraulic heads for layer 3
$outpath//$flowx3grid # (new) grid for fluxes in x direction for layer 3
$Writegrid # writecode for flux-x-grid in layer 3
$outpath//$flowy3grid # (new) grid for fluxes in y direction for layer 3
$Writegrid # writecode for flux-y-grid in layer 3
$outpath//$GWbalance3grid # (new) grid for balance (difference of storage change vs. balance of fluxes -> should be 0 or the amount of in-/outflows by boundary conditions
13 # writecode for balance control grid in layer 3 (should be at least one sum grid per year --> Code = 20 or 23 (if old grids must be read in)

this paragraph is not needed for WaSiM-uzr but for the WaSiM-version with the variable saturated area approach (after Topmodel)

[soil_model]
1 # 0=ignore this module, 1 = run the module
$time # duration of a time step in minutes
1 # method, 1 = without slow baseflow, 2 = with slow baseflow (not recommended)
$outpath//$sat_def_grid # (new) saturation deficite-grid (in mm)
$Writegrid # writegrid for this grid
$outpath//$SUZgrid # (new) storage grid for unsat. zone
$Writegrid # writegrid for this grid
$outpath//$SIFgrid # (new) storage grid for interflow storage
$Writegrid # writegrid for this grid
$outpath//$SBiagrid # (new) grid for soil moisture in the inaktive soil storage
$Writegrid # Writegrid for inaktive soil moisture
$outpath//$fcia_grid # (new) grid for plant available field capacity in the inaktiven soil storage
$Writegrid # writegrid for this grid
$outpath//$SSPgrid # (new) grid for the relative fraction of the soil storages, which is in contact with ground water
$Writegrid # writegrid for this grid
$outpath//$QDgrid # (new) grid for surface runoff
$Writegrid # writegrid for this grid
$outpath//$QIgrid # (new) grid for Interflow
$Writegrid # writegrid for this grid
$outpath//$Peakgrid # (new) grid for Peakflow (maximum peakflow for the entire model time)
$outpath//qdir//$grid//.//$code//$year $once_per_interval # statistic of the surfeca discharge
$outpath//qifl//$grid//.//$code//$year $once_per_interval # statistic of the Interflows
$outpath//qbas//$grid//.//$code//$year $once_per_interval # statistic of the base flow
$outpath//qbav//$grid//.//$code//$year $once_per_interval # statistic of the slow base flow
$outpath//qges//$grid//.//$code//$year $once_per_interval # statistic of the total discharge
$outpath//sb__//$grid//.//$code//$year $once_per_interval # soil storage in mm per zone
$outpath//suz_//$grid//.//$code//$year $once_per_interval # drainage storage in mm per zone
$outpath//sifl//$grid//.//$code//$year $once_per_interval # interflow storage in mm per zone
$outpath//sd__//$grid//.//$code//$year $once_per_interval # saturation deficite per zone in mm
10 # Codes der Teilgebiete im Zonengrid
0.015 # Rezessionsparameterter m fuer Saettigungsflaechenmodell in Metern
40.0 # Korrekturfaktor fuer Transmissivitaeten
8.0 # Korrekturfaktor fuer K-Wert (vertikale Versickerung), Modell erwartet k in m/s
6.0 # Speicherrueckgangskonstante Direktabflus ELS in h
0.0 # Saettigungsdefizit, bei dessen Unterschreitung lokaler Interflow gebildet wird
1.0 # Speicherrueckgangskonstante Interflow ELS in h
3600 # Rueckgangskonstante verzoegerter Basisabfluss in h
0.03 # maximale Tiefenversickerungsrate bei Saettigung in mm/h
0.01 # Anfangswert QBB
0.0 # Anfangsfuellung des SUZ-Speichers in n*nFK
0.45 # Anfangssaettigungsdefizit in n*nFK, beeinflusst den ersten Basisabfluss

3.0 # Anspringpunkt fuer Makroporenabfluss (in mm/h!, bezogen auf Stundenniederschlag!), alles darueber geht direkt in den Drainspeicher!
0.9 # Reduktionsfaktor fuer Auffuellung von Verdunstungsverlusten aus dem Grundwasser und aus dem Interflowspeicher
0.4 # Anteil an der effektiven Schneeschmelze, der bei geschlossener Schneedecke direkt abfliesst und nicht in den Boden gelangen kann
$readgrids # 1=read grids from disk, else generate internal
$outpath//storage_topmodel.ftz # if readgrids = 1, then this file contains the contents of the flow travel time zones for interflow and surface flow and for the tracers

[routing_model]
1 # 0=ignore this module, 1 = run the module, 2=run the module with observed inflows into the routing channels (from discharge files)
$time # duration of a time step in minutes
1 1200 90 24 # minimum/maximum specific discharge (l/s/km^2), number of log. fractions of the range, splitting of the timeintervall (24= 1 hour-intervalls are splitted into 24 Intervalls each of 2.5 min. duration)
$outpath//qgko//$grid//.//$code//$year $routing_code # name of the statistic file with routed discharges
$inpath_hydro//test.dat # name of the file with observed discharges (mm/Timestep or m^3/s)
1 # number of following collumn descriptor
1 1 # if the first code would be a 7, then it would mean, that the modeled discharge of 1 (or lowest subbasin code) would communicate with the data column 7 in the specific discharge data file (date-columns are not counted!)
720 # timeoffset (for r-square calculation. intervals up to this parameter are not evaluated in r-square calculation. e.g. 12: first 12 intervals are neglected)

TG 22 (AE=70.078, AErel=1.0)
from OL 11 (kh=0.1, kv=0.4, Bh=11.9, Bv= 47.4, Th= 1.19, Mh=20.0, Mv= 8.0, I=0.0032, L=6019.8, AE=52.157)
TG 33 (AE=72.013, AErel=1.0)
from OL 22 (kh=0.1, kv=0.4, Bh=12.5, Bv= 50.1, Th= 1.25, Mh=20.0, Mv= 8.0, I=0.0043, L=2352.1, AE=70.078)

[abstraction_rule_abstraction_1]
0

[abstraction_rule_abstraction_2]
0

[abstraction_rule_reservoir_1]
0

[multilayer_landuse]
10 # count of multilayer landuses
1 extensive grassland { Landuse_Layers = 1, -9999, -9999; k_extinct = 0.3; LAI_scale = 20;}
2 arrable and horticulture { Landuse_Layers = 2, -9999, -9999; k_extinct = 0.3; LAI_scale = 20;}
3 coniferous wodland { Landuse_Layers = 3, 4, -9999; k_extinct = 0.3; LAI_scale = 20;}
4 dwarf shrub heath { Landuse_Layers = 4, -9999, -9999; k_extinct = 0.3; LAI_scale = 20;}
5 acid grassland { Landuse_Layers = 5, -9999, -9999; k_extinct = 0.3; LAI_scale = 20;}
6 broad leaved, mixed and yew woodland { Landuse_Layers = 6, 10, -9999; k_extinct = 0.3; LAI_scale = 20;}

7 built up areas and gardens { Landuse_Layers = 7, -9999, -9999; k_extinct = 0.3; LAI_scale = 20;}
8 montane habitats { Landuse_Layers = 4, -9999, -9999; k_extinct = 0.3; LAI_scale = 20;}
9 freshwater { Landuse_Layers = 9, -9999, -9999; k_extinct = 0.3; LAI_scale = 20;}
10 rough low productivity grassland { Landuse_Layers = 1, -9999, -9999; k_extinct = 0.3; LAI_scale = 20;}

[landuse_table]
10 # number of following land use codes
1 extensive_grassland {method = VariableDayCount;
RootDistr = 1.0;
TReduWet = 0.95;
LimitReduWet = 0.5;
HReduDry = 3.5;
IntercepCap = 0.4;
JulDays = 15 46 74 105 135 166 196 227 258 288 319 349 ;
Albedo = 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 ;
rsc = 90 90 80 70 60 55 50 55 60 70 90 90 ;
rs_interception = 5 5 5 5 5 5 5 5 5 5 5 5 ;
rs_evaporation = 600 600 600 600 600 600 600 600 600 600 600 600 ;
LAI = 2 2 2 2 3 3 3 3 3 2 2 2 ;
Z0 = 0.03 0.03 0.03 0.04 0.04 0.04 0.04 0.04 0.04 0.03 0.03 0.03 ;
VCF = 0.8 0.8 0.8 0.9 0.9 0.9 0.9 0.9 0.8 0.8 0.8 0.8 ;
RootDepth = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
AltDep = 0.025 0.025 0.025 0.025 0.025 0.025 -0.025 -0.025 -0.025 -0.025 -0.025 -0.025;
}
2 agriculture {method = VariableDayCount;
RootDistr = 1.0;
TReduWet = 0.95;
LimitReduWet = 0.5;
HReduDry = 3.5;
IntercepCap = 0.4;
JulDays = 15 46 74 105 135 166 196 227 258 288 319 349 ;
Albedo = 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 ;
rsc = 80 80 75 75 65 55 55 55 65 75 90 90 ;
rs_interception = 5 5 5 5 5 5 5 5 5 5 5 5 ;
rs_evaporation = 200 200 200 200 200 200 200 200 200 200 200 200 ;
LAI = 1 1 2 3 4 5 5 4 3 2 1 1 ;
Z0 = 0.03 0.03 0.03 0.04 0.05 0.05 0.05 0.05 0.04 0.03 0.03 0.03 ;
VCF = 0.3 0.3 0.3 0.7 0.8 0.95 0.95 0.8 0.7 0.3 0.3 0.3 ;
RootDepth = 0.15 0.15 0.2 0.4 0.5 0.5 0.5 0.5 0.4 0.2 0.15 0.15 ;

AltDep = 0.025 0.025 0.025 0.025 0.025 0.025 -0.025 -0.025 -0.025 -0.025 -0.025 -0.025;
}
3 coniferous_forest {method = VariableDayCount;
RootDistr = 1.0;
TReduWet = 0.95;
LimitReduWet = 0.5;
HReduDry = 3.5;
IntercepCap = 0.6;
JulDays = 15 46 74 105 135 166 196 227 258 288 319 349 ;
Albedo = 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 ;
rsc = 80 80 75 65 55 55 55 55 55 75 80 80 ;
rs_interception = 5 5 5 5 5 5 5 5 5 5 5 5 ;
rs_evaporation = 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 ;
LAI = 6 6 8 8 10 10 10 10 8 8 6 6 ;
Z0 = 3 3 3 3 3 3 3 3 3 3 3 3 ;
VCF = 0.9 0.9 0.9 0.9 0.95 0.95 0.95 0.95 0.95 0.9 0.9 0.9 ;
RootDepth = 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 ;
AltDep = 0.025 0.025 0.025 0.025 0.025 0.025 -0.025 -0.025 -0.025 -0.025 -0.025 -0.025;
}
4 dwarf_shrub {method = VariableDayCount;
RootDistr = 1.0;
TReduWet = 0.95;
LimitReduWet = 0.5;
HReduDry = 3.5;
IntercepCap = 0.6;
JulDays = 15 46 74 105 135 166 196 227 258 288 319 349 ;
Albedo = 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 ;
rsc = 80 80 70 70 60 50 50 60 60 70 70 80 ;
rs_interception = 5 5 5 5 5 5 5 5 5 5 5 5 ;
rs_evaporation = 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 ;
LAI = 3 3 3 4 5 5 4 4 3 3 3 3 ;
Z0 = 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 ;
VCF = 0.9 0.9 0.9 0.9 0.95 0.95 0.95 0.95 0.95 0.9 0.9 0.9 ;
RootDepth = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
AltDep = 0.025 0.025 0.025 0.025 0.025 0.025 -0.025 -0.025 -0.025 -0.025 -0.025 -0.025;
}
5 acid_grassland {method = VariableDayCount;
RootDistr = 1.0;
TReduWet = 0.95;
LimitReduWet = 0.5;
HReduDry = 3.5;
IntercepCap = 0.4;
JulDays = 15 46 74 105 135 166 196 227 258 288 319 349 ;

Albedo = 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 ;
rsc = 90 90 80 70 60 55 50 55 60 70 90 90 ;
rs_interception = 5 5 5 5 5 5 5 5 5 5 5 5 ;
rs_evaporation = 600 600 600 600 600 600 600 600 600 600 600 600 ;
LAI = 2 2 2 2 3 3 3 3 3 2 2 2 ;
Z0 = 0.03 0.03 0.03 0.04 0.04 0.04 0.04 0.04 0.04 0.03 0.03 0.03 ;
VCF = 0.8 0.8 0.8 0.9 0.9 0.9 0.9 0.9 0.8 0.8 0.8 0.8 ;
RootDepth = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
AltDep = 0.025 0.025 0.025 0.025 0.025 0.025 -0.025 -0.025 -0.025 -0.025 -0.025 -0.025;
}
6 decidous_forest {method = VariableDayCount;
RootDistr = 1.0;
TReduWet = 0.95;
LimitReduWet = 0.5;
HReduDry = 3.5;
IntercepCap = 0.6;
JulDays = 15 46 74 105 135 166 196 227 258 288 319 349 ;
Albedo = 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 ;
rsc = 100 100 95 75 65 65 65 65 65 85 100 100 ;
rs_interception = 5 5 5 5 5 5 5 5 5 5 5 5 ;
rs_evaporation = 1500 1500 1500 1500 1500 1500 1500 1500 1500 1500 1500 1500 ;
LAI = 1 1 4 4 6 7 7 6 5 4 1 1 ;
Z0 = 2 2 2 2 2 2 2 2 2 2 2 2 ;
VCF = 0.7 0.7 0.7 0.8 0.95 0.95 0.95 0.95 0.9 0.8 0.7 0.7 ;
RootDepth = 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 ;
AltDep = 0.025 0.025 0.025 0.025 0.025 0.025 -0.025 -0.025 -0.025 -0.025 -0.025 -0.025;
}
7 settlements {method = VariableDayCount;
RootDistr = 1.0;
TReduWet = 0.95;
LimitReduWet = 0.5;
HReduDry = 3.5;
IntercepCap = 0.2;
JulDays = 15 46 74 105 135 166 196 227 258 288 319 349 ;
Albedo = 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 ;
rsc = 100 100 100 100 100 100 100 100 100 100 100 100 ;
rs_interception = 5 5 5 5 5 5 5 5 5 5 5 5 ;
rs_evaporation = 200 200 200 200 200 200 200 200 200 200 200 200 ;
LAI = 1 1 1 1 1 1 1 1 1 1 1 1 ;
Z0 = 1 1 1 1 1 1 1 1 1 1 1 1 ;
VCF = 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 ;

```
                RootDepth      = 0.2   0.2   0.2   0.2   0.2   0.2    0.2    0.2    0.2    0.2
0.2    0.2  ;
                AltDep         = 0.025 0.025 0.025 0.025 0.025 0.025 -0.025 -0.025 -
0.025 -0.025 -0.025 -0.025;
                }
8 montane_habitat {method   = VariableDayCount;
                RootDistr       = 1.0;
                TReduWet        = 0.95;
                LimitReduWet    = 0.5;
                HReduDry        = 3.5;
                IntercepCap     = 0.4;
                JulDays         = 15    46    74    105    135    166    196    227    258    288
319    349  ;
                Albedo          = 0.25  0.25  0.25  0.25  0.25  0.25   0.25   0.25   0.25
0.25   0.25   0.25 ;
                rsc             = 90    90    80    75    70    65     60     65     70     80     90     90
;
                rs_interception  = 5     5     5     5     5     5      5      5      5      5      5      5  ;
                rs_evaporation   = 1000  1000  1000  1000  1000  1000   1000   1000
1000   1000   1000   1000 ;
                LAI             = 2     2     2     2     2     2      2      2      2      2      2      2    ;
                Z0              = 0.03  0.03  0.03  0.04  0.04  0.04   0.04   0.04   0.04   0.03
0.03   0.03 ;
                VCF             = 0.7   0.7   0.7   0.8   0.8   0.8    0.8    0.8    0.7    0.7    0.7
0.7  ;
                RootDepth       = 0.4   0.4   0.4   0.4   0.4   0.4    0.4    0.4    0.4    0.4
0.4    0.4  ;
                AltDep          = 0.025 0.025 0.025 0.025 0.025 0.025 -0.025 -0.025 -
0.025 -0.025 -0.025 -0.025;
                }
9  water              {method  = VariableDayCount;
                      RootDistr          = 1;
                      TReduWet           = 1;
                      LimitReduWet       = 1;
                      HReduDry           = 150;
                      IntercepCap        = 0;
                      JulDays  = 365;
                      Albedo             = 0.1;
                      rsc                = 0.1;
                      rs_interception = 0;
                      rs_evaporation     = 0;
                      LAI                = 0;
                      Z0                 = 0.3;
                      VCF                = 0;
                      RootDepth          = 0;
                      AltDep   = 0;
                }
10 woodland_grassland {method   = VariableDayCount;
                RootDistr       = 1.0;
                TReduWet        = 0.95;
                LimitReduWet    = 0.5;
                HReduDry        = 3.5;
                IntercepCap     = 0.4;
                JulDays         = 15    46    74    105    135    166    196    227    258    288
319    349  ;
                Albedo          = 0.25  0.25  0.25  0.25  0.25  0.25   0.25   0.25   0.25
0.25   0.25   0.25 ;
                rsc             = 90    90    80    70    60    55     50     55     60     70     90     90
;
                rs_interception  = 5     5     5     5     5     5      5      5      5      5      5      5  ;
```

rs_evaporation = 600 600 600 600 600 600 600 600 600 600 600 600 ;
LAI = 2 2 2 2 3 3 3 3 3 2 2 2 ;
Z0 = 0.03 0.03 0.03 0.04 0.04 0.04 0.04 0.04 0.04 0.03 0.03 0.03 ;
VCF = 0.8 0.8 0.8 0.9 0.9 0.9 0.9 0.9 0.8 0.8 0.8 0.8 ;
RootDepth = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
AltDep = 0.025 0.025 0.025 0.025 0.025 0.025 -0.025 -0.025 -0.025 -0.025 -0.025 -0.025;
}
[soil_table]
40 # number of following entries
11 humus_iron_podzols_gleys_(S) {method = MultipleHorizons;
PMacroThresh = 1000 ; # precipitation capacity thresholding macropore runoff in mm per hour (not in
MacroCapacity = 1 ; # capacity of the macropores in mm per hour (not in "m/s," because it's more convenient than to write it down in "m/s," e.g. 5mm/h = 1.38e-6)
CapacityRedu = 0.5 ; # reduction of the macropore capacity with depth -> pores become less dense. This Factor describes the reduction ratio per meter
MacroDepth = 1 ; # maximum depth of the macropores
horizon = 1 2 3 4 5 6 7 ; # ID of the horizon (must be ascendent) it's recommended to name the horizons shortly in the following row
Name = Ap Bs BCx C x xy qqq ; # short descriptions
ksat = 4.39E-06 7.93E-06 5.61E-06 6.83E-06 6.83E-06 6.83E-06 6.83E-06 ; # saturated hydraulic conductivity in m/s
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ; # k sat recession with depth (could also be controlled by different layers if no k decrease is wanted (set this parameter to 1
theta_sat = 0.386 0.386 0.382 0.383 0.383 0.383 0.383 ; # saturated water content (fillable porosity in 1/1)
theta_res = 0.043 0.039 0.045 0.042 0.042 0.042 0.042 ; # residual water content (in "1/1," water content which cannot be poured by "transpiration," only by evaporation)
alpha = 3.06 3.99 3.53 3.75 3.75 3.75 3.75 ; # van Genuchten Parameter Alpha
Par_n = 1.4 1.53 1.45 1.49 1.49 1.49 1.49 ; # van Genuchten Parameter n
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ; # sog. Mualem-Parameter tau in der van-Genuchten-Gleichung (dort normalerweise 0.5)
thickness = 0.25 0.15 0.25 0.35 0.15 0.15 1.4 ; # thickness of each single numerical layer in this horizon in m
layers = 1 1 1 1 1 1 3 ; # numerical number of layers in this horizon. The thickness of the layer is given by layers x thickness. All profiles must have an identical number of layers (for memory handling reasons only)
}
12 humus_iron_podzols_gleys_(S) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bs BCx C x xy qqq ;
ksat = 8.78E-06 1.59E-05 1.12E-05 1.37E-05 1.37E-05 1.37E-05 1.37E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.386 0.386 0.382 0.383 0.383 0.383 0.383 ;
theta_res = 0.043 0.039 0.045 0.042 0.042 0.042 0.042 ;
alpha = 3.06 3.99 3.53 3.75 3.75 3.75 3.75 ;
Par_n = 1.4 1.53 1.45 1.49 1.49 1.49 1.49 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.15 0.25 0.35 0.15 0.15 1.4 ;

```
layers = 1 1 1 1 1 1 3 ;
}
13 humus_iron_podzols_gleys_(S) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bs BCx C x xy qqq ;
ksat = 2.20E-05 3.97E-05 2.81E-05 3.42E-05 3.42E-05 3.42E-05 3.42E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.386 0.386 0.382 0.383 0.383 0.383 0.383 ;
theta_res = 0.043 0.039 0.045 0.042 0.042 0.042 0.042 ;
alpha = 3.06 3.99 3.53 3.75 3.75 3.75 3.75 ;
Par_n = 1.4 1.53 1.45 1.49 1.49 1.49 1.49 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.15 0.25 0.35 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
14 humus_iron_podzols_gleys_(S) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bs BCx C x xy qqq ;
ksat = 3.51E-05 6.34E-05 4.49E-05 5.46E-05 5.46E-05 5.46E-05 5.46E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.386 0.386 0.382 0.383 0.383 0.383 0.383 ;
theta_res = 0.043 0.039 0.045 0.042 0.042 0.042 0.042 ;
alpha = 3.06 3.99 3.53 3.75 3.75 3.75 3.75 ;
Par_n = 1.4 1.53 1.45 1.49 1.49 1.49 1.49 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.15 0.25 0.35 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
15 humus_iron_podzols_gleys_(S) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bs BCx C x xy qqq ;
ksat = 4.39E-06 7.93E-06 5.61E-06 6.83E-06 6.83E-06 6.83E-06 6.83E-06 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.386 0.386 0.382 0.383 0.383 0.383 0.383 ;
theta_res = 0.043 0.039 0.045 0.042 0.042 0.042 0.042 ;
alpha = 3.06 3.99 3.53 3.75 3.75 3.75 3.75 ;
Par_n = 1.4 1.53 1.45 1.49 1.49 1.49 1.49 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.15 0.25 0.35 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
21 brown_forest_soils1_(S) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bw Bx BC C x qqq ;
```

```
ksat = 3.11E-06 3.84E-06 6.22E-06 3.29E-06 6.57E-06 6.57E-06 6.57e-6;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.39 0.387 0.392 0.386 0.386 0.386 0.386 ;
theta_res = 0.044 0.043 0.033 0.049 0.04 0.04 0.04 ;
alpha = 1.65 2.42 3.03 2.64 3.81 3.81 3.81 ;
Par_n = 1.44 1.4 1.41 1.39 1.47 1.47 1.47 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.3 0.15 0.15 0.15 0.25 0.3 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
22 brown_forest_soils1_(S) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bw Bx BC C x qqq ;
ksat = 6.22E-06 7.68E-06 1.24E-05 6.58E-06 1.31E-05 1.31E-05 1.31E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.39 0.387 0.392 0.386 0.386 0.386 0.386 ;
theta_res = 0.044 0.043 0.033 0.049 0.04 0.04 0.04 ;
alpha = 1.65 2.42 3.03 2.64 3.81 3.81 3.81 ;
Par_n = 1.44 1.4 1.41 1.39 1.47 1.47 1.47 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.3 0.15 0.15 0.15 0.25 0.3 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
23 brown_forest_soils1_(S) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bw Bx BC C x qqq ;
ksat = 1.56E-05 1.92E-05 3.11E-05 1.65E-05 3.29E-05 3.29E-05 3.29E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.39 0.387 0.392 0.386 0.386 0.386 0.386 ;
theta_res = 0.044 0.043 0.033 0.049 0.04 0.04 0.04 ;
alpha = 1.65 2.42 3.03 2.64 3.81 3.81 3.81 ;
Par_n = 1.44 1.4 1.41 1.39 1.47 1.47 1.47 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.3 0.15 0.15 0.15 0.25 0.3 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
24 brown_forest_soils1_(S) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bw Bx BC C x qqq ;
ksat = 2.49E-05 3.07E-05 4.98E-05 2.63E-05 5.26E-05 5.26E-05 5.26E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.39 0.387 0.392 0.386 0.386 0.386 0.386 ;
theta_res = 0.044 0.043 0.033 0.049 0.04 0.04 0.04 ;
alpha = 1.65 2.42 3.03 2.64 3.81 3.81 3.81 ;
Par_n = 1.44 1.4 1.41 1.39 1.47 1.47 1.47 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.3 0.15 0.15 0.15 0.25 0.3 1.4 ;
layers = 1 1 1 1 1 1 3 ;
```

```
}
25 brown_forest_soils1_(S) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bw Bx BC C x qqq ;
ksat = 3.11E-06 3.84E-06 6.22E-06 3.29E-06 6.57E-06 6.57E-06 6.57e-6;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.39 0.387 0.392 0.386 0.386 0.386 0.386 ;
theta_res = 0.044 0.043 0.033 0.049 0.04 0.04 0.04 ;
alpha = 1.65 2.42 3.03 2.64 3.81 3.81 3.81 ;
Par_n = 1.44 1.4 1.41 1.39 1.47 1.47 1.47 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.3 0.15 0.15 0.15 0.25 0.3 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
31 humus_iron_gleys2_(SL) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bsh BC C x xy qqq ;
ksat = 4.40E-06 5.48E-06 4.77E-06 5.39E-06 5.39E-06 5.39E-06 5.39e-6;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.387 0.388 0.386 0.388 0.388 0.388 0.388 ;
theta_res = 0.041 0.038 0.042 0.038 0.038 0.038 0.038 ;
alpha = 2.77 3.28 3.19 3.18 3.18 3.18 3.18 ;
Par_n = 1.4 1.41 1.41 1.41 1.41 1.41 1.41 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.15 0.25 0.25 0.35 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
32 humus_iron_gleys2_(SL) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bsh BC C x xy qqq ;
ksat = 8.80E-06 1.10E-05 9.54E-06 1.08E-05 1.08E-05 1.08E-05 1.08E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.387 0.388 0.386 0.388 0.388 0.388 0.388 ;
theta_res = 0.041 0.038 0.042 0.038 0.038 0.038 0.038 ;
alpha = 2.77 3.28 3.19 3.18 3.18 3.18 3.18 ;
Par_n = 1.4 1.41 1.41 1.41 1.41 1.41 1.41 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.15 0.25 0.25 0.35 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
33 humus_iron_gleys2_(SL) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bsh BC C x xy qqq ;
ksat = 2.20E-05 2.74E-05 2.39E-05 2.70E-05 2.70E-05 2.70E-05 2.70E-05 ;
```

```
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.387 0.388 0.386 0.388 0.388 0.388 0.388 ;
 theta_res = 0.041 0.038 0.042 0.038 0.038 0.038 0.038 ;
 alpha = 2.77 3.28 3.19 3.18 3.18 3.18 3.18 ;
 Par_n = 1.4 1.41 1.41 1.41 1.41 1.41 1.41 ;
 Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
 thickness = 0.15 0.25 0.25 0.35 0.15 0.15 1.4 ;
 layers = 1 1 1 1 1 1 3 ;
 }
34 humus_iron_gleys2_(SL) {method = MultipleHorizons;
 PMacroThresh = 1000 ;
 MacroCapacity = 1 ;
 CapacityRedu = 0.5 ;
 MacroDepth = 1 ;
 horizon = 1 2 3 4 5 6 7 ;
 Name = Ap Bsh BC C x xy qqq ;
 ksat = 3.52E-05 4.38E-05 3.82E-05 4.31E-05 4.31E-05 4.31E-05 4.31E-05 ;
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.387 0.388 0.386 0.388 0.388 0.388 0.388 ;
 theta_res = 0.041 0.038 0.042 0.038 0.038 0.038 0.038 ;
 alpha = 2.77 3.28 3.19 3.18 3.18 3.18 3.18 ;
 Par_n = 1.4 1.41 1.41 1.41 1.41 1.41 1.41 ;
 Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
 thickness = 0.15 0.25 0.25 0.35 0.15 0.15 1.4 ;
 layers = 1 1 1 1 1 1 3 ;
 }
35 humus_iron_gleys2_(SL) {method = MultipleHorizons;
 PMacroThresh = 1000 ;
 MacroCapacity = 1 ;
 CapacityRedu = 0.5 ;
 MacroDepth = 1 ;
 horizon = 1 2 3 4 5 6 7 ;
 Name = Ap Bsh BC C x xy qqq ;
 ksat = 4.40E-06 5.48E-06 4.77E-06 5.39E-06 5.39E-06 5.39E-06 5.39e-6;
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.387 0.388 0.386 0.388 0.388 0.388 0.388 ;
 theta_res = 0.041 0.038 0.042 0.038 0.038 0.038 0.038 ;
 alpha = 2.77 3.28 3.19 3.18 3.18 3.18 3.18 ;
 Par_n = 1.4 1.41 1.41 1.41 1.41 1.41 1.41 ;
 Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
 thickness = 0.15 0.25 0.25 0.35 0.15 0.15 1.4 ;
 layers = 1 1 1 1 1 1 3 ;
 }
42 peaty_podzols_gleys1_(SIL) {method = MultipleHorizons;
 PMacroThresh = 1000 ;
 MacroCapacity = 1 ;
 CapacityRedu = 0.5 ;
 MacroDepth = 1 ;
 horizon = 1 2 3 4 5 6 7 ;
 Name = O E Bh Bs BCx C qqq ;
 ksat = 2.50E-05 1.97E-05 2.50E-05 1.67E-05 1.51E-05 2.78E-05 2.78E-05 ;
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.391 0.388 0.391 0.387 0.386 0.387 0.387 ;
 theta_res = 0.035 0.037 0.035 0.037 0.039 0.039 0.039 ;
 alpha = 4.54 4.26 4.54 4.12 3.98 4.26 4.26 ;
 Par_n = 1.73 1.61 1.73 1.54 1.51 1.81 1.81 ;
 Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
 thickness = 0.25 0.1 0.05 0.25 0.2 0.15 1.5 ;
 layers = 1 1 1 1 1 1 3 ;
 }
```

43 peaty_podzols_gleys1_(SIL) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = O E Bh Bs BCx C qqq ;
ksat = 6.25E-05 4.92E-05 6.25E-05 4.18E-05 3.78E-05 6.95E-05 6.95E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.391 0.388 0.391 0.387 0.386 0.387 0.387 ;
theta_res = 0.035 0.037 0.035 0.037 0.039 0.039 0.039 ;
alpha = 4.54 4.26 4.54 4.12 3.98 4.26 4.26 ;
Par_n = 1.73 1.61 1.73 1.54 1.51 1.81 1.81 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.1 0.05 0.25 0.2 0.15 1.5 ;
layers = 1 1 1 1 1 1 3 ;
}
44 peaty_podzols_gleys1_(SIL) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = O E Bh Bs BCx C qqq ;
ksat = 1.00E-04 7.87E-05 1.00E-04 6.69E-05 6.04E-05 1.11E-04 1.11E-04 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.391 0.388 0.391 0.387 0.386 0.387 0.387 ;
theta_res = 0.035 0.037 0.035 0.037 0.039 0.039 0.039 ;
alpha = 4.54 4.26 4.54 4.12 3.98 4.26 4.26 ;
Par_n = 1.73 1.61 1.73 1.54 1.51 1.81 1.81 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.1 0.05 0.25 0.2 0.15 1.5 ;
layers = 1 1 1 1 1 1 3 ;
}
45 peaty_podzols_gleys1_(SIL) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = O E Bh Bs BCx C qqq ;
ksat = 1.25E-05 9.84E-06 1.25E-05 8.36E-06 7.55E-06 1.39E-05 1.39E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.391 0.388 0.391 0.387 0.386 0.387 0.387 ;
theta_res = 0.035 0.037 0.035 0.037 0.039 0.039 0.039 ;
alpha = 4.54 4.26 4.54 4.12 3.98 4.26 4.26 ;
Par_n = 1.73 1.61 1.73 1.54 1.51 1.81 1.81 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.1 0.05 0.25 0.2 0.15 1.5 ;
layers = 1 1 1 1 1 1 3 ;
}
51 brown_forest_soils2_(SC) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap B BCx C x xy qqq ;
ksat = 2.95E-06 8.95E-06 5.69E-06 6.83E-06 6.83E-06 6.83E-06 6.83E-06 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;

```
theta_sat = 0.388 0.395 0.384 0.382 0.382 0.382 0.382 ;
theta_res = 0.049 0.03 0.043 0.045 0.045 0.045 0.045 ;
alpha = 2.24 4.37 3.59 3.63 3.63 3.63 3.63 ;
Par_n = 1.4 1.49 1.44 1.5 1.5 1.5 1.5 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.21 0.15 0.39 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
52 brown_forest_soils2_(SC) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap B BCx C x xy qqq ;
ksat = 5.90E-06 1.79E-05 1.14E-05 1.37E-05 1.37E-05 1.37E-05 1.37E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.388 0.395 0.384 0.382 0.382 0.382 0.382 ;
theta_res = 0.049 0.03 0.043 0.045 0.045 0.045 0.045 ;
alpha = 2.24 4.37 3.59 3.63 3.63 3.63 3.63 ;
Par_n = 1.4 1.49 1.44 1.5 1.5 1.5 1.5 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.21 0.15 0.39 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
53 brown_forest_soils2_(SC) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap B BCx C x xy qqq ;
ksat = 1.48E-05 4.48E-05 2.85E-05 3.42E-05 3.42E-05 3.42E-05 3.42E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.388 0.395 0.384 0.382 0.382 0.382 0.382 ;
theta_res = 0.049 0.03 0.043 0.045 0.045 0.045 0.045 ;
alpha = 2.24 4.37 3.59 3.63 3.63 3.63 3.63 ;
Par_n = 1.4 1.49 1.44 1.5 1.5 1.5 1.5 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.21 0.15 0.39 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
54 brown_forest_soils2_(SC) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap B BCx C x xy qqq ;
ksat = 2.36E-05 7.16E-05 4.55E-05 5.46E-05 5.46E-05 5.46E-05 5.46E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.388 0.395 0.384 0.382 0.382 0.382 0.382 ;
theta_res = 0.049 0.03 0.043 0.045 0.045 0.045 0.045 ;
alpha = 2.24 4.37 3.59 3.63 3.63 3.63 3.63 ;
Par_n = 1.4 1.49 1.44 1.5 1.5 1.5 1.5 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.21 0.15 0.39 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
55 brown_forest_soils2_(SC) {method = MultipleHorizons;
```

PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap B BCx C x xy qqq ;
ksat = 2.95E-06 8.95E-06 5.69E-06 6.83E-06 6.83E-06 6.83E-06 6.83E-06 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.388 0.395 0.384 0.382 0.382 0.382 0.382 ;
theta_res = 0.049 0.03 0.043 0.045 0.045 0.045 0.045 ;
alpha = 2.24 4.37 3.59 3.63 3.63 3.63 3.63 ;
Par_n = 1.4 1.49 1.44 1.5 1.5 1.5 1.5 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.25 0.21 0.15 0.39 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
61 alluvial_soil_(C) {method = MultipleHorizons;
PMacroThresh = 1000 ; # precipitation capacity thresholding macropore runoff in mm per hour (not in "m/s," because it's more convenient than to write it down in "m/s," e.g. 5mm/h = 1.38e-6)
MacroCapacity = 4 ;
CapacityRedu = 1 ;
MacroDepth = 1.5 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Apg Bg Cg x xy xyz qqq ;
ksat = 2.75E-06 2.39E-06 5.48E-06 5.48E-06 5.48E-06 5.48E-06 5.48E-06 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.39 0.391 0.388 0.388 0.388 0.388 0.388 ;
theta_res = 0.045 0.05 0.038 0.038 0.038 0.038 0.038 ;
alpha = 1.57 1.63 3.28 3.28 3.28 3.28 3.28 ;
Par_n = 1.44 1.43 1.41 1.41 1.41 1.41 1.41 ;
thickness = 0.25 0.25 0.5 0.2 0.2 0.2 1.3 ;
layers = 1 1 1 1 1 1 3 ;
}
62 alluvial_soil_(C) {method = MultipleHorizons;
PMacroThresh = 1000 ; # precipitation capacity thresholding macropore runoff in mm per hour (not in "m/s," because it's more convenient than to write it down in "m/s," e.g. 5mm/h = 1.38e-6)
MacroCapacity = 4 ;
CapacityRedu = 1 ;
MacroDepth = 1.5 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Apg Bg Cg x xy xyz qqq ;
ksat = 5.50E-06 4.78E-06 1.10E-05 1.10E-05 1.10E-05 1.10E-05 1.10E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.39 0.391 0.388 0.388 0.388 0.388 0.388 ;
theta_res = 0.045 0.05 0.038 0.038 0.038 0.038 0.038 ;
alpha = 1.57 1.63 3.28 3.28 3.28 3.28 3.28 ;
Par_n = 1.44 1.43 1.41 1.41 1.41 1.41 1.41 ;
thickness = 0.25 0.25 0.5 0.2 0.2 0.2 1.3 ;
layers = 1 1 1 1 1 1 3 ;
}
63 alluvial_soil_(C) {method = MultipleHorizons;
PMacroThresh = 1000 ; # precipitation capacity thresholding macropore runoff in mm per hour (not in "m/s," because it's more convenient than to write it down in "m/s," e.g. 5mm/h = 1.38e-6)
MacroCapacity = 4 ;
CapacityRedu = 1 ;
MacroDepth = 1.5 ;
horizon = 1 2 3 4 5 6 7 ;

Name = Apg Bg Cg x xy xyz qqq ;
ksat = 1.38E-05 1.20E-05 2.74E-05 2.74E-05 2.74E-05 2.74E-05 2.74E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.39 0.391 0.388 0.388 0.388 0.388 0.388 ;
theta_res = 0.045 0.05 0.038 0.038 0.038 0.038 0.038 ;
alpha = 1.57 1.63 3.28 3.28 3.28 3.28 3.28 ;
Par_n = 1.44 1.43 1.41 1.41 1.41 1.41 1.41 ;
thickness = 0.25 0.25 0.5 0.2 0.2 0.2 1.3 ;
layers = 1 1 1 1 1 1 3 ;
}
64 alluvial_soil_(C) {method = MultipleHorizons;
PMacroThresh = 1000 ; # precipitation capacity thresholding macropore runoff in mm per hour (not in "m/s," because it's more convenient than to write it down in "m/s," e.g. 5mm/h = 1.38e-6)
MacroCapacity = 4 ;
CapacityRedu = 1 ;
MacroDepth = 1.5 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Apg Bg Cg x xy xyz qqq ;
ksat = 2.20E-05 1.91E-05 4.38E-05 4.38E-05 4.38E-05 4.38E-05 4.38E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.39 0.391 0.388 0.388 0.388 0.388 0.388 ;
theta_res = 0.045 0.05 0.038 0.038 0.038 0.038 0.038 ;
alpha = 1.57 1.63 3.28 3.28 3.28 3.28 3.28 ;
Par_n = 1.44 1.43 1.41 1.41 1.41 1.41 1.41 ;
thickness = 0.25 0.25 0.5 0.2 0.2 0.2 1.3 ;
layers = 1 1 1 1 1 1 3 ;
}
65 alluvial_soil_(C) {method = MultipleHorizons;
PMacroThresh = 1000 ; # precipitation capacity thresholding macropore runoff in mm per hour (not in "m/s," because it's more convenient than to write it down in "m/s," e.g. 5mm/h = 1.38e-6)
MacroCapacity = 4 ;
CapacityRedu = 1 ;
MacroDepth = 1.5 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Apg Bg Cg x xy xyz qqq ;
ksat = 2.75E-06 2.39E-06 5.48E-06 5.48E-06 5.48E-06 5.48E-06 5.48E-06 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.39 0.391 0.388 0.388 0.388 0.388 0.388 ;
theta_res = 0.045 0.05 0.038 0.038 0.038 0.038 0.038 ;
alpha = 1.57 1.63 3.28 3.28 3.28 3.28 3.28 ;
Par_n = 1.44 1.43 1.41 1.41 1.41 1.41 1.41 ;
thickness = 0.25 0.25 0.5 0.2 0.2 0.2 1.3 ;
layers = 1 1 1 1 1 1 3 ;
}
71 humus_iron_podzols1_(M) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bs BC C x xy qqq ;
ksat = 7.55E-06 3.07E-05 2.36E-05 1.75E-05 1.75E-05 1.75E-05 1.75e-5;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.384 0.381 0.383 0.388 0.388 0.388 0.388 ;
theta_res = 0.041 0.047 0.044 0.039 0.039 0.039 0.039 ;
alpha = 3.87 3.67 3.85 4.29 4.29 4.29 4.29 ;
Par_n = 1.52 2.37 2.17 1.96 1.96 1.96 1.96 ;

```
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.3 0.35 0.15 0.2 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
72 humus_iron_podzols1_(M) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bs BC C x xy qqq ;
ksat = 1.51E-05 6.14E-05 4.72E-05 3.50E-05 3.50E-05 3.50E-05 0.000035 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.384 0.381 0.383 0.388 0.388 0.388 0.388 ;
theta_res = 0.041 0.047 0.044 0.039 0.039 0.039 0.039 ;
alpha = 3.87 3.67 3.85 4.29 4.29 4.29 4.29 ;
Par_n = 1.52 2.37 2.17 1.96 1.96 1.96 1.96 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.3 0.35 0.15 0.2 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
73 humus_iron_podzols1_(M) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bs BC C x xy qqq ;
ksat = 3.78E-05 1.54E-04 1.18E-04 8.75E-05 8.75E-05 8.75E-05 8.75E-05 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.384 0.381 0.383 0.388 0.388 0.388 0.388 ;
theta_res = 0.041 0.047 0.044 0.039 0.039 0.039 0.039 ;
alpha = 3.87 3.67 3.85 4.29 4.29 4.29 4.29 ;
Par_n = 1.52 2.37 2.17 1.96 1.96 1.96 1.96 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.3 0.35 0.15 0.2 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
74 humus_iron_podzols1_(M) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
horizon = 1 2 3 4 5 6 7 ;
Name = Ap Bs BC C x xy qqq ;
ksat = 6.04E-05 2.46E-04 1.89E-04 1.40E-04 1.40E-04 1.40E-04 1.40E-04 ;
k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
theta_sat = 0.384 0.381 0.383 0.388 0.388 0.388 0.388 ;
theta_res = 0.041 0.047 0.044 0.039 0.039 0.039 0.039 ;
alpha = 3.87 3.67 3.85 4.29 4.29 4.29 4.29 ;
Par_n = 1.52 2.37 2.17 1.96 1.96 1.96 1.96 ;
Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
thickness = 0.3 0.35 0.15 0.2 0.15 0.15 1.4 ;
layers = 1 1 1 1 1 1 3 ;
}
75 humus_iron_podzols1_(M) {method = MultipleHorizons;
PMacroThresh = 1000 ;
MacroCapacity = 1 ;
CapacityRedu = 0.5 ;
MacroDepth = 1 ;
```

```
 horizon = 1 2 3 4 5 6 7 ;
 Name = Ap Bs BC C x xy qqq ;
 ksat = 7.55E-06 3.07E-05 2.36E-05 1.75E-05 1.75E-05 1.75E-05 1.75e-5;
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.384 0.381 0.383 0.388 0.388 0.388 0.388 ;
 theta_res = 0.041 0.047 0.044 0.039 0.039 0.039 0.039 ;
 alpha = 3.87 3.67 3.85 4.29 4.29 4.29 4.29 ;
 Par_n = 1.52 2.37 2.17 1.96 1.96 1.96 1.96 ;
 Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
 thickness = 0.3 0.35 0.15 0.2 0.15 0.15 1.4 ;
 layers = 1 1 1 1 1 1 3 ;
 }
80 open_water_(M) {method = MultipleHorizons;
 PMacroThresh = 1000 ; # precipitation capacity thresholding macropore runoff in mm per hour (not in "m/s," because it's more convenient than to write it down in "m/s," e.g. 5mm/h = 1.38e-6)
 MacroCapacity = 4 ;
 CapacityRedu = 1 ;
 MacroDepth = 1.5 ;
 horizon = 1 2 3 4 5 6 7 ;
 Name = SI10m SI10m x xy xyz xyzw qqq ;
 ksat = 4.00E-06 4.00E-06 4.00E-06 4.00E-06 4.00E-06 4.00E-06 4.0e-6;
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.45 0.45 0.45 0.45 0.45 0.45 0.45 ;
 theta_res = 0.08 0.08 0.08 0.08 0.08 0.08 0.08 ;
 alpha = 5.2 5.2 5.2 5.2 5.2 5.2 5.2 ;
 Par_n = 1.33 1.33 1.33 1.33 1.33 1.33 1.33 ;
 thickness = 0.1 0.1 0.15 0.15 0.15 0.15 1.6 ;
 layers = 1 1 1 1 1 1 3 ;
 }
91 humus_iron_podzols_alluvial_(M) {method = MultipleHorizons;
 PMacroThresh = 1000 ;
 MacroCapacity = 1 ;
 CapacityRedu = 0.5 ;
 MacroDepth = 1 ;
 horizon = 1 2 3 4 5 6 7 ;
 Name = H E Bh Bs BC C qqq ;
 ksat = 1.46E-05 1.05E-05 1.52E-05 2.09E-05 7.70E-05 5.07E-05 5.07e-5;
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.389 0.387 0.386 0.384 0.379 0.382 0.382 ;
 theta_res = 0.037 0.038 0.04 0.043 0.05 0.046 0.046 ;
 alpha = 4.43 4.23 4.19 3.94 3.48 3.74 3.74 ;
 Par_n = 1.83 1.65 1.86 2.08 3.27 2.85 2.85 ;
 Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
 thickness = 0.15 0.05 0.05 0.2 0.15 0.4 1.5 ;
 layers = 1 1 1 1 1 1 3 ;
 }
92 humus_iron_podzols_alluvial_(M) {method = MultipleHorizons;
 PMacroThresh = 1000 ;
 MacroCapacity = 1 ;
 CapacityRedu = 0.5 ;
 MacroDepth = 1 ;
 horizon = 1 2 3 4 5 6 7 ;
 Name = H E Bh Bs BC C qqq ;
 ksat = 2.92E-05 2.10E-05 3.04E-05 4.18E-05 1.54E-04 1.01E-04 0.0001014 ;
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.389 0.387 0.386 0.384 0.379 0.382 0.382 ;
 theta_res = 0.037 0.038 0.04 0.043 0.05 0.046 0.046 ;
 alpha = 4.43 4.23 4.19 3.94 3.48 3.74 3.74 ;
 Par_n = 1.83 1.65 1.86 2.08 3.27 2.85 2.85 ;
```

```
 Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
 thickness = 0.15 0.05 0.05 0.2 0.15 0.4 1.5 ;
 layers = 1 1 1 1 1 1 3 ;
 }
93 humus_iron_podzols_alluvial_(M) {method = MultipleHorizons;
 PMacroThresh = 1000 ;
 MacroCapacity = 1 ;
 CapacityRedu = 0.5 ;
 MacroDepth = 1 ;
 horizon = 1 2 3 4 5 6 7 ;
 Name = H E Bh Bs BC C qqq ;
 ksat = 7.30E-05 5.25E-05 7.60E-05 1.05E-04 3.85E-04 2.54E-04 2.54E-04 ;
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.389 0.387 0.386 0.384 0.379 0.382 0.382 ;
 theta_res = 0.037 0.038 0.04 0.043 0.05 0.046 0.046 ;
 alpha = 4.43 4.23 4.19 3.94 3.48 3.74 3.74 ;
 Par_n = 1.83 1.65 1.86 2.08 3.27 2.85 2.85 ;
 Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
 thickness = 0.15 0.05 0.05 0.2 0.15 0.4 1.5 ;
 layers = 1 1 1 1 1 1 3 ;
 }
94 humus_iron_podzols_alluvial_(M) {method = MultipleHorizons;
 PMacroThresh = 1000 ;
 MacroCapacity = 1 ;
 CapacityRedu = 0.5 ;
 MacroDepth = 1 ;
 horizon = 1 2 3 4 5 6 7 ;
 Name = H E Bh Bs BC C qqq ;
 ksat = 1.17E-04 8.40E-05 1.22E-04 1.67E-04 6.16E-04 4.06E-04 4.06E-04 ;
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.389 0.387 0.386 0.384 0.379 0.382 0.382 ;
 theta_res = 0.037 0.038 0.04 0.043 0.05 0.046 0.046 ;
 alpha = 4.43 4.23 4.19 3.94 3.48 3.74 3.74 ;
 Par_n = 1.83 1.65 1.86 2.08 3.27 2.85 2.85 ;
 Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
 thickness = 0.15 0.05 0.05 0.2 0.15 0.4 1.5 ;
 layers = 1 1 1 1 1 1 3 ;
 }
95 humus_iron_podzols_alluvial_(M) {method = MultipleHorizons;
 PMacroThresh = 1000 ;
 MacroCapacity = 1 ;
 CapacityRedu = 0.5 ;
 MacroDepth = 1 ;
 horizon = 1 2 3 4 5 6 7 ;
 Name = H E Bh Bs BC C qqq ;
 ksat = 1.46E-05 1.05E-05 1.52E-05 2.09E-05 7.70E-05 5.07E-05 5.07e-5;
 k_recession = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 ;
 theta_sat = 0.389 0.387 0.386 0.384 0.379 0.382 0.382 ;
 theta_res = 0.037 0.038 0.04 0.043 0.05 0.046 0.046 ;
 alpha = 4.43 4.23 4.19 3.94 3.48 3.74 3.74 ;
 Par_n = 1.83 1.65 1.86 2.08 3.27 2.85 2.85 ;
 Par_tau = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 ;
 thickness = 0.15 0.05 0.05 0.2 0.15 0.4 1.5 ;
 layers = 1 1 1 1 1 1 3 ;
 }


[substance_transport]
0    # number of tracers to be considered (max. 9)
```

```
[irrigation_table]
0               # number of following irrigation codes, per row one use

[special_output]
0   # 0=do not run this module, 1=run this module
$time   # duration of a time step in minutes --> only for compatibility here.
numfiles = 2;
outputfile { header = glacierdata;
 filename = $outpath//special_output_glaciers.//$code//$year;
 entity {
  ID  = GlacierMassBalance;
  Symbol  = GMB;
  Xcoords = 771371, 801115, 771211;
  Ycoords = 214666, 194848, 164323;
 }
 entity {
  ID  = melt_from_firn;
  Symbol  = Mfirn;
  Xcoords = 771371, 801115, 771211;
  Ycoords = 214666, 194848, 164323;
 }
 entity {
  ID  = melt_from_ice;
  Symbol  = Mice;
  Xcoords = 771371, 801115, 771211;
  Ycoords = 214666, 194848, 164323;
 }
}
outputfile { header = soildata;
 filename = $outpath//special_output_soilmodel.//$code//$year;
 entity {
  ID  = theta;
  Symbol  = th;
  Xcoords = 748503, 748503, 748503, 748503, 748503, 748503, 770572, 770572,
770572, 770572, 770572, 770572;
  Ycoords = 196127, 196127, 196127, 196127, 196127, 196127, 256698, 256698,
256698, 256698, 256698, 256698;
  Level = 1,    2,    3,    4,   5,    6,    1,   2,   3,   4,   5,   6;
 }
 entity {
  ID  = hydraulic_heads;
  Symbol  = hh;
  Xcoords = 748503, 748503, 748503, 748503, 748503, 748503, 770572, 770572,
770572, 770572, 770572, 770572;
  Ycoords = 196127, 196127, 196127, 196127, 196127, 196127, 256698, 256698,
256698, 256698, 256698, 256698;
  Level = 1,    2,    3,    4,   5,    6,    1,   2,   3,   4,   5,   6;
 }
}
```

Appendix C

Table A3.1. Design events

Duration	Event period	baseline	2020s	2050s	2080s
7 hour	10 years	38.58	41.43	43.3	44.20
	100 years	60.57	66.75	70.98	71.84
15 hour	10 years	48.19	52.64	55.39	57.39
	100 years	76.43	85.92	90.88	96.64

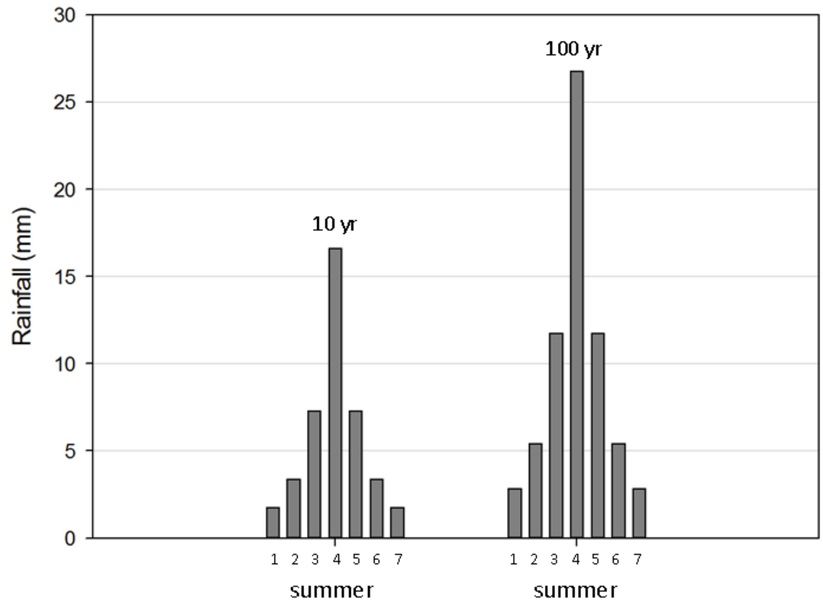


Figure A3.1. Design rainfall events for 7 hour duration event with summer profile for the 2020s

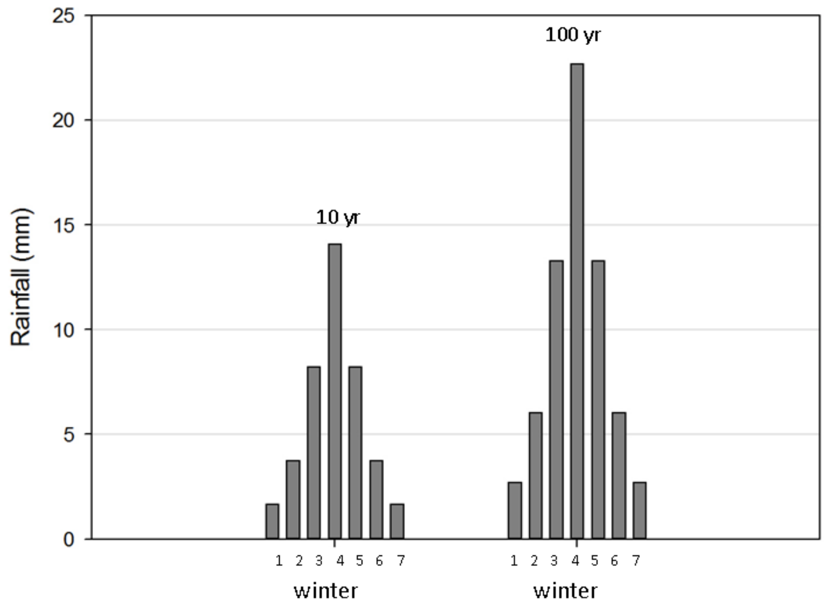


Figure A3.2. Design rainfall events for 7 hour duration event with winter profile for the 2020s

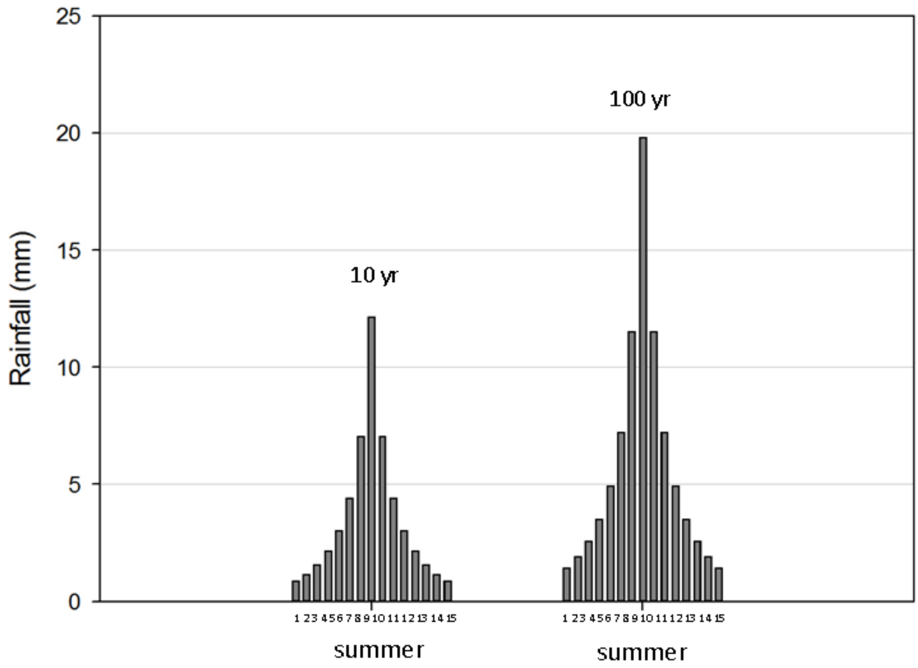


Figure A3.3. Design rainfall events for 15 hour duration event with summer profile for the 2020s

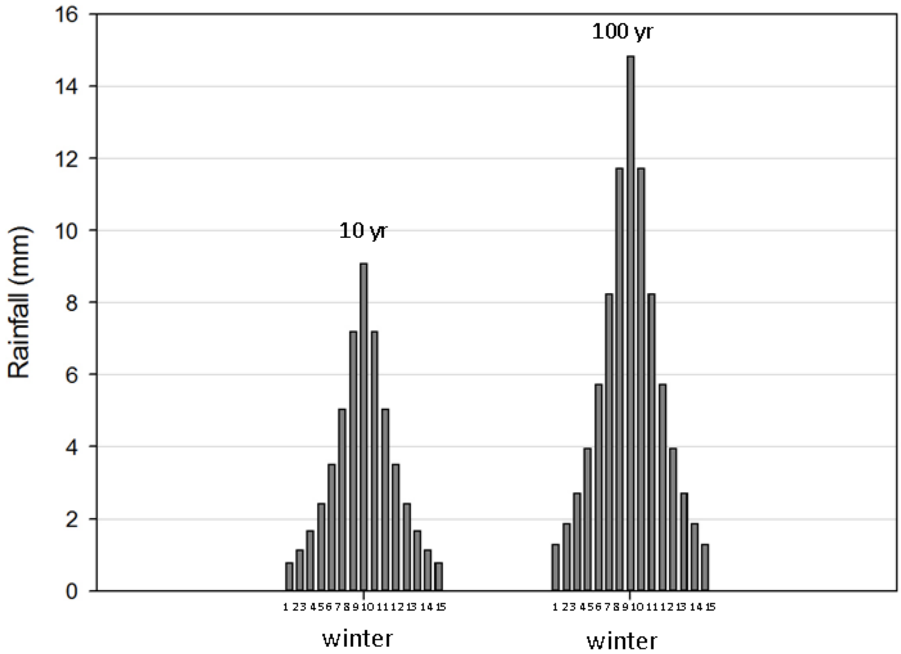


Figure A3.4. Design rainfall events for 15 hour duration event with winter profile for the 2020s

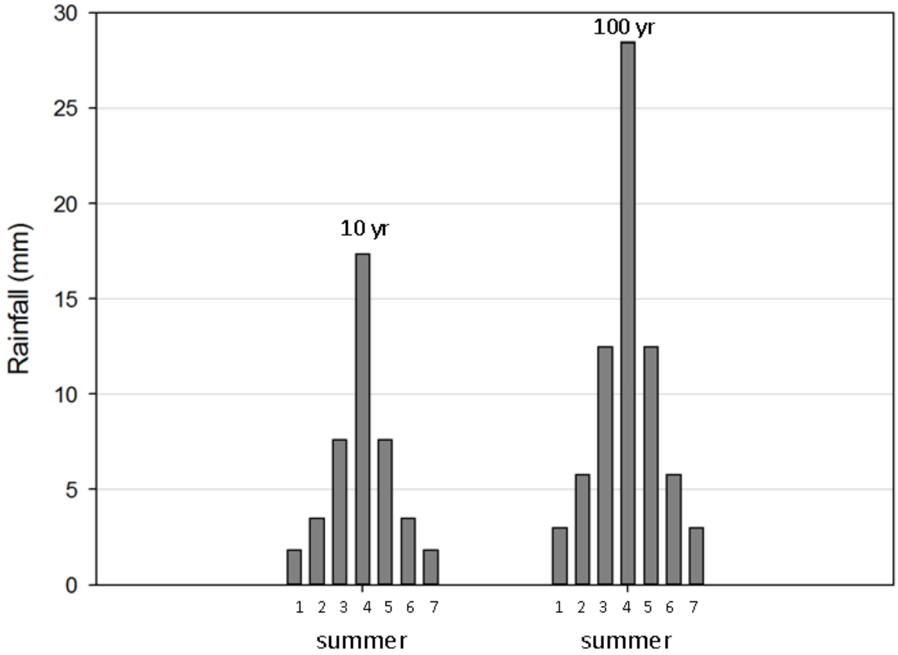


Figure A3.5. Design rainfall events for 7 hour duration event with summer profile for the 2050s

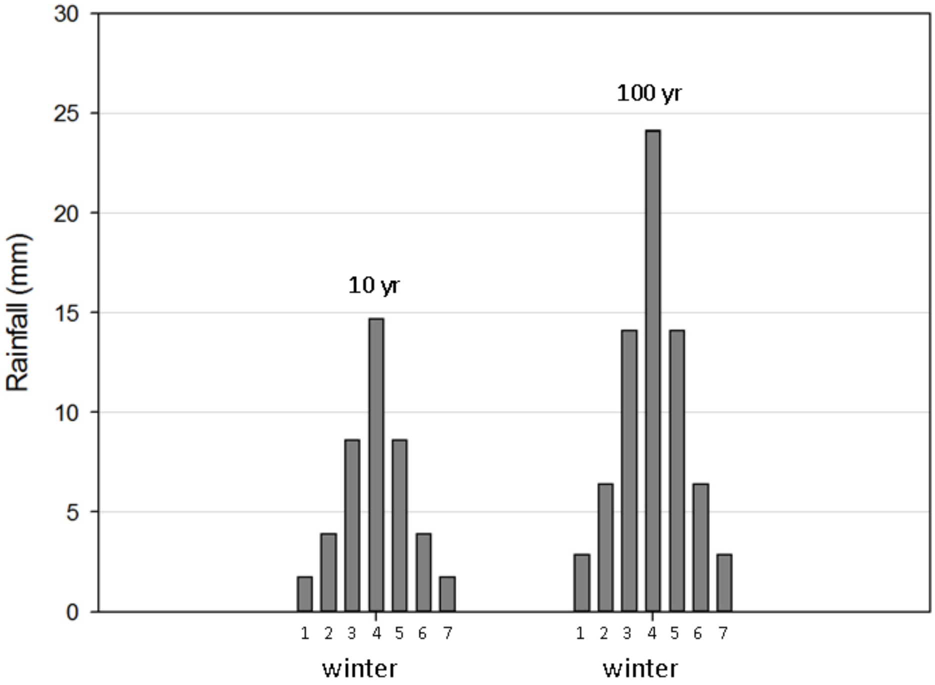


Figure A3.6. Design rainfall events for 7 hour duration event with winter profile for the 2050s

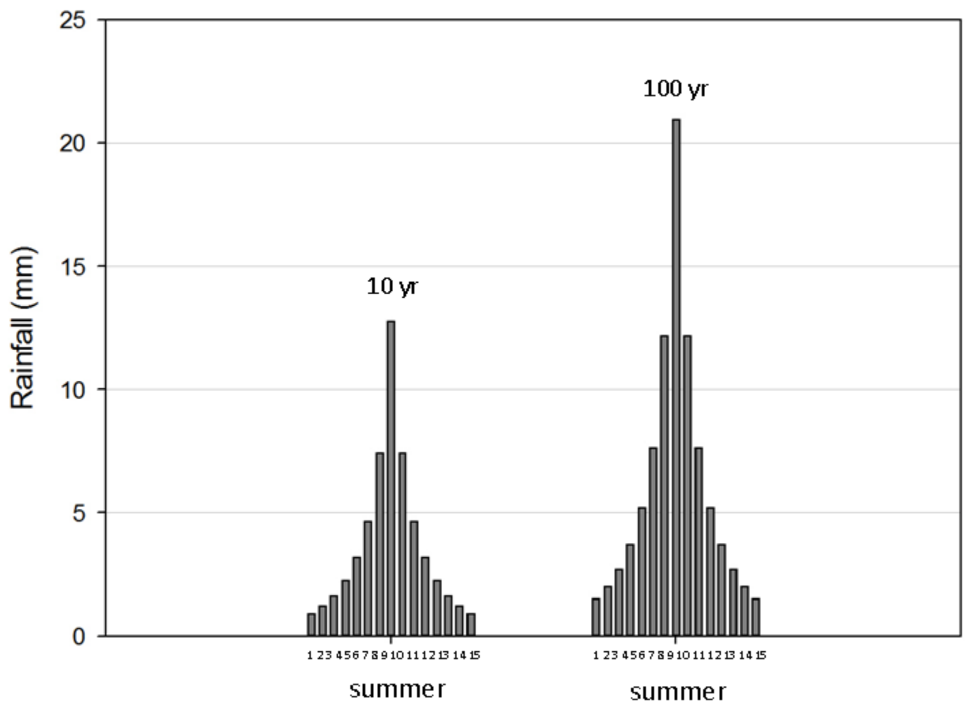


Figure A3.74. Design rainfall events for 15 hour duration event with summer profile for the 2050s

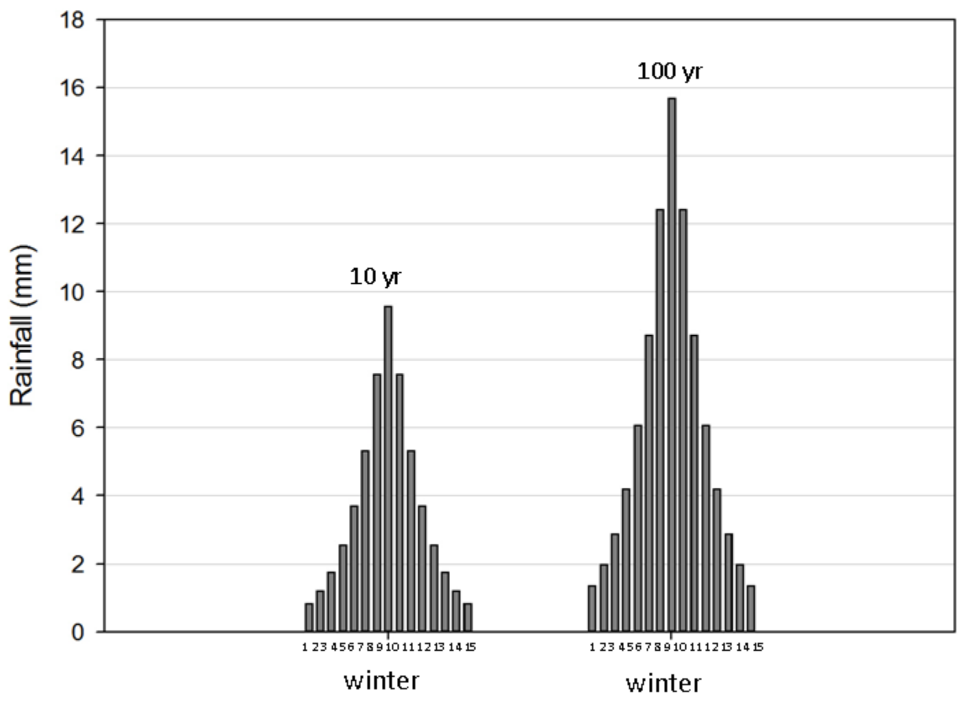


Figure A3.8. Design rainfall events for 15 hour duration event with winter profile for the 2050s

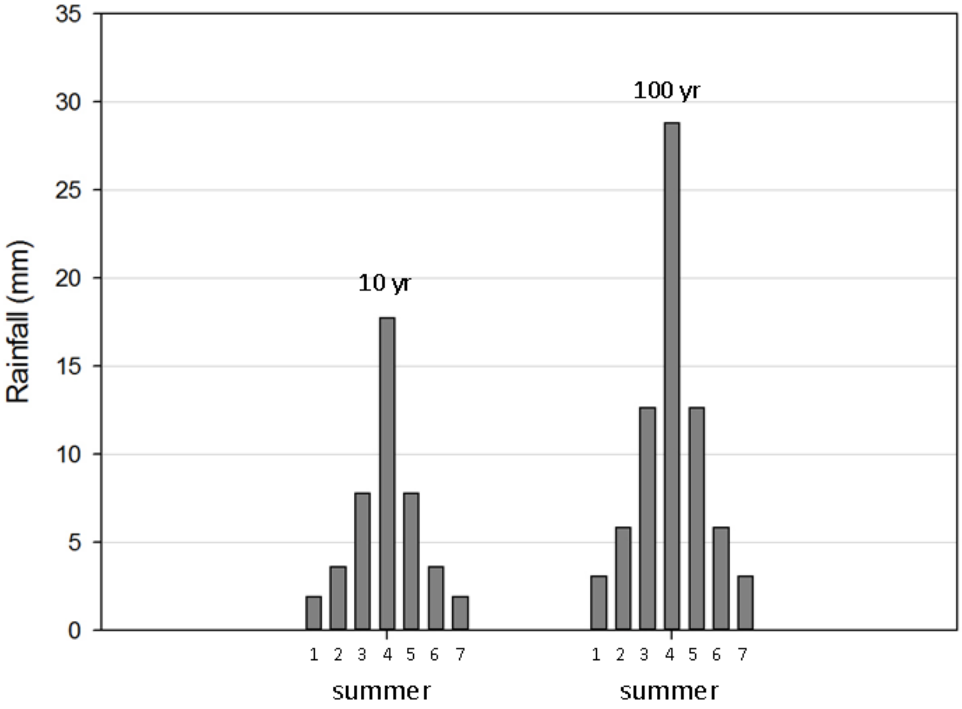


Figure A3.9. Design rainfall events for 7 hour duration event with summer profile for the 2080s

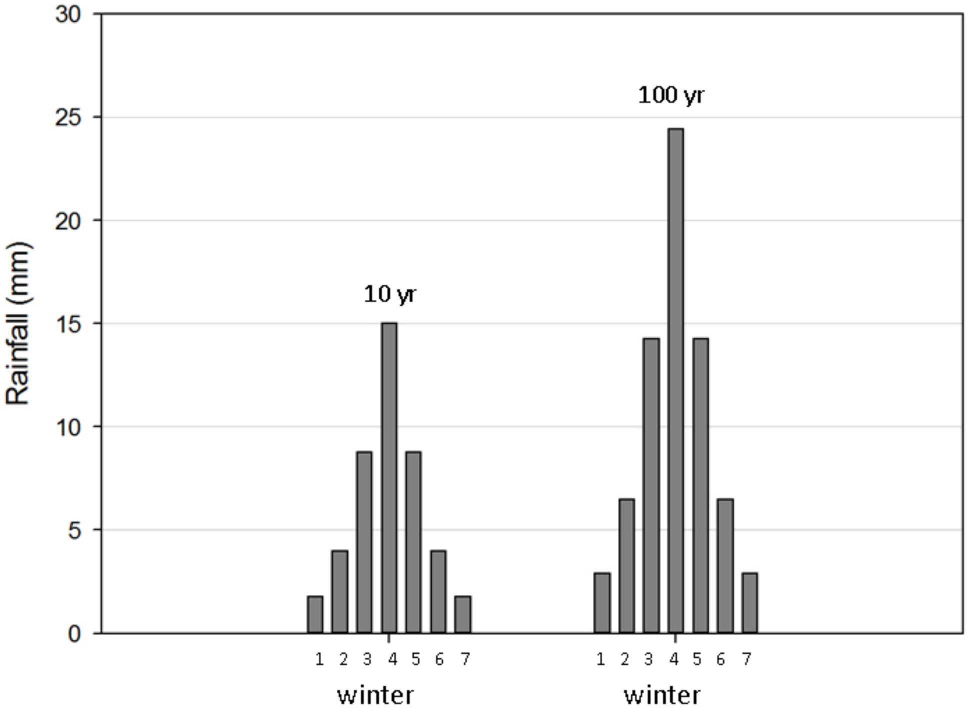


Figure A3.10. Design rainfall events for 7 hour duration event with winter profile for the 2080s

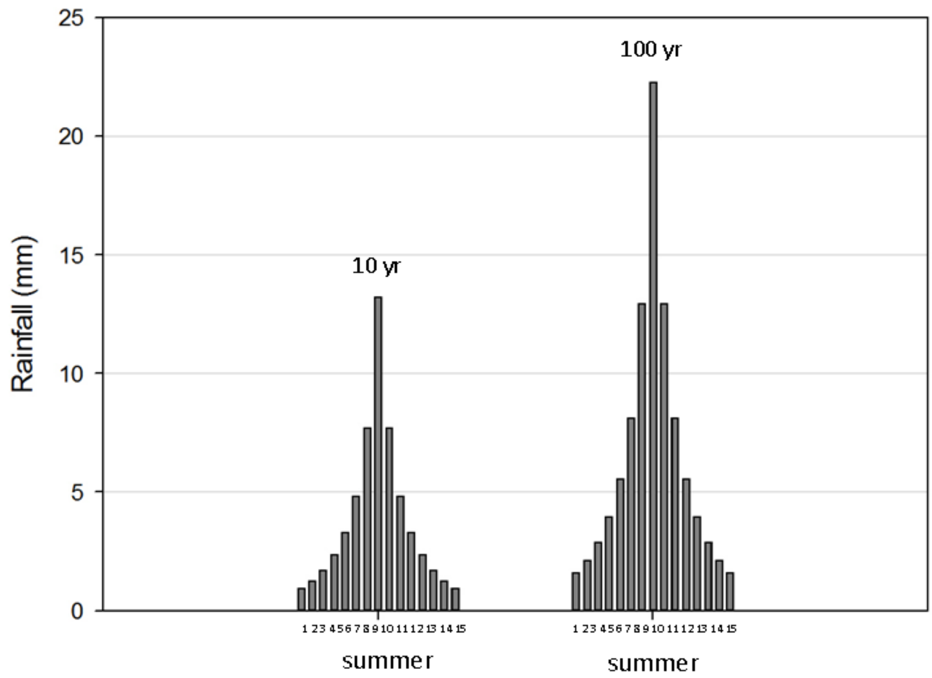


Figure A3.11. Design rainfall events for 15 hour duration event with summer profile for the 2080s

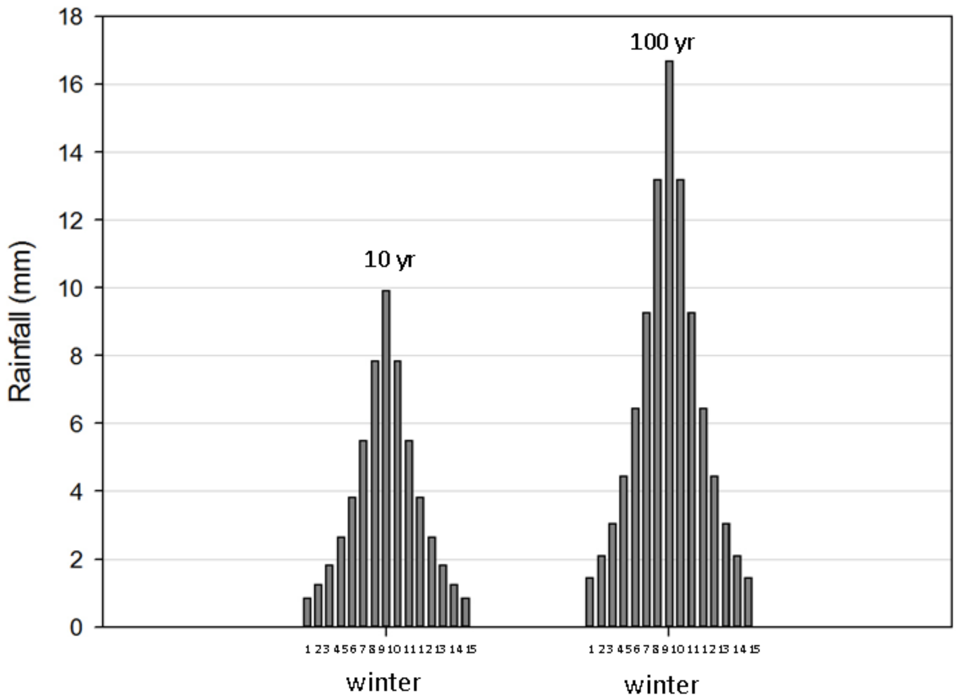
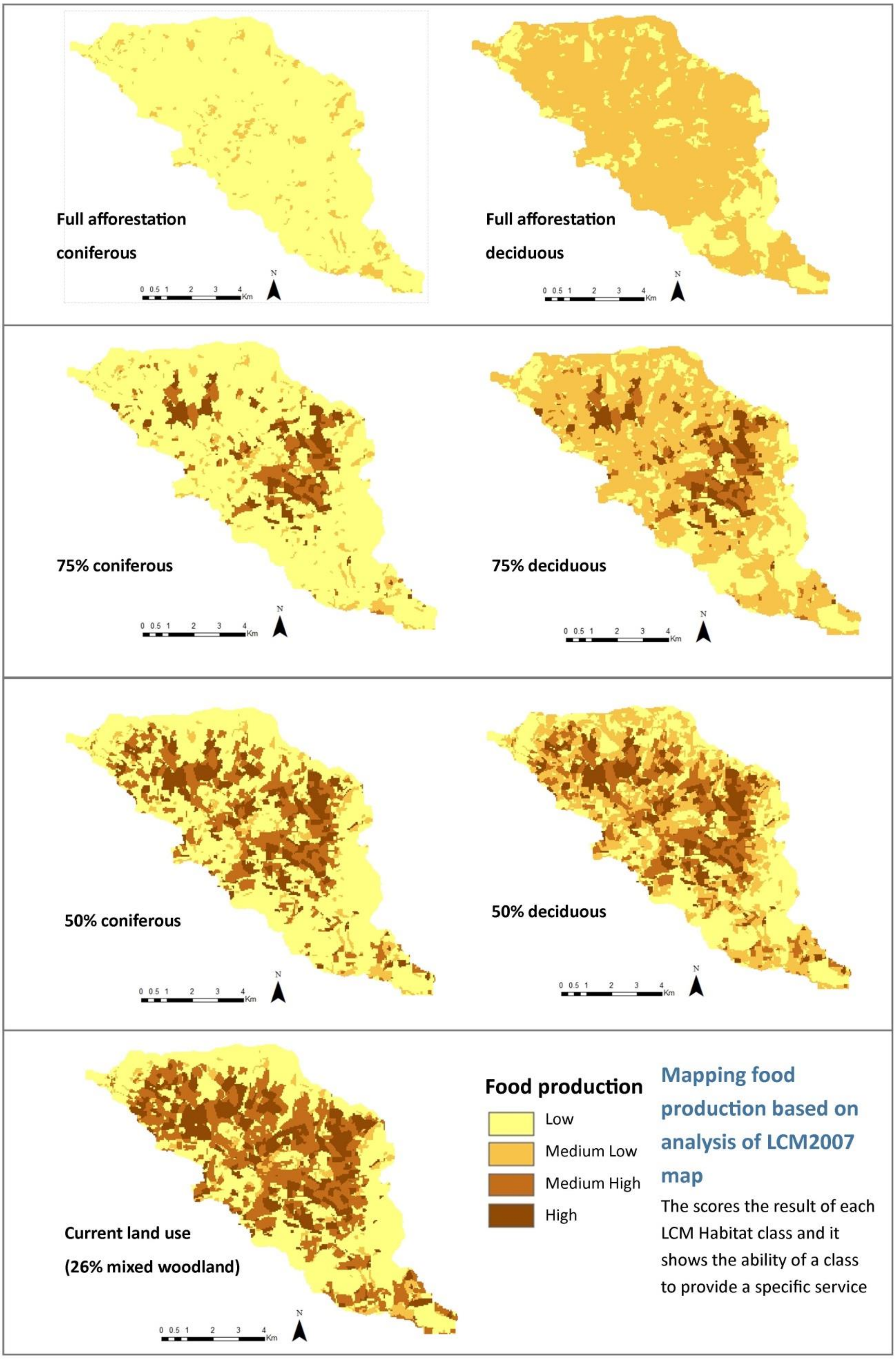
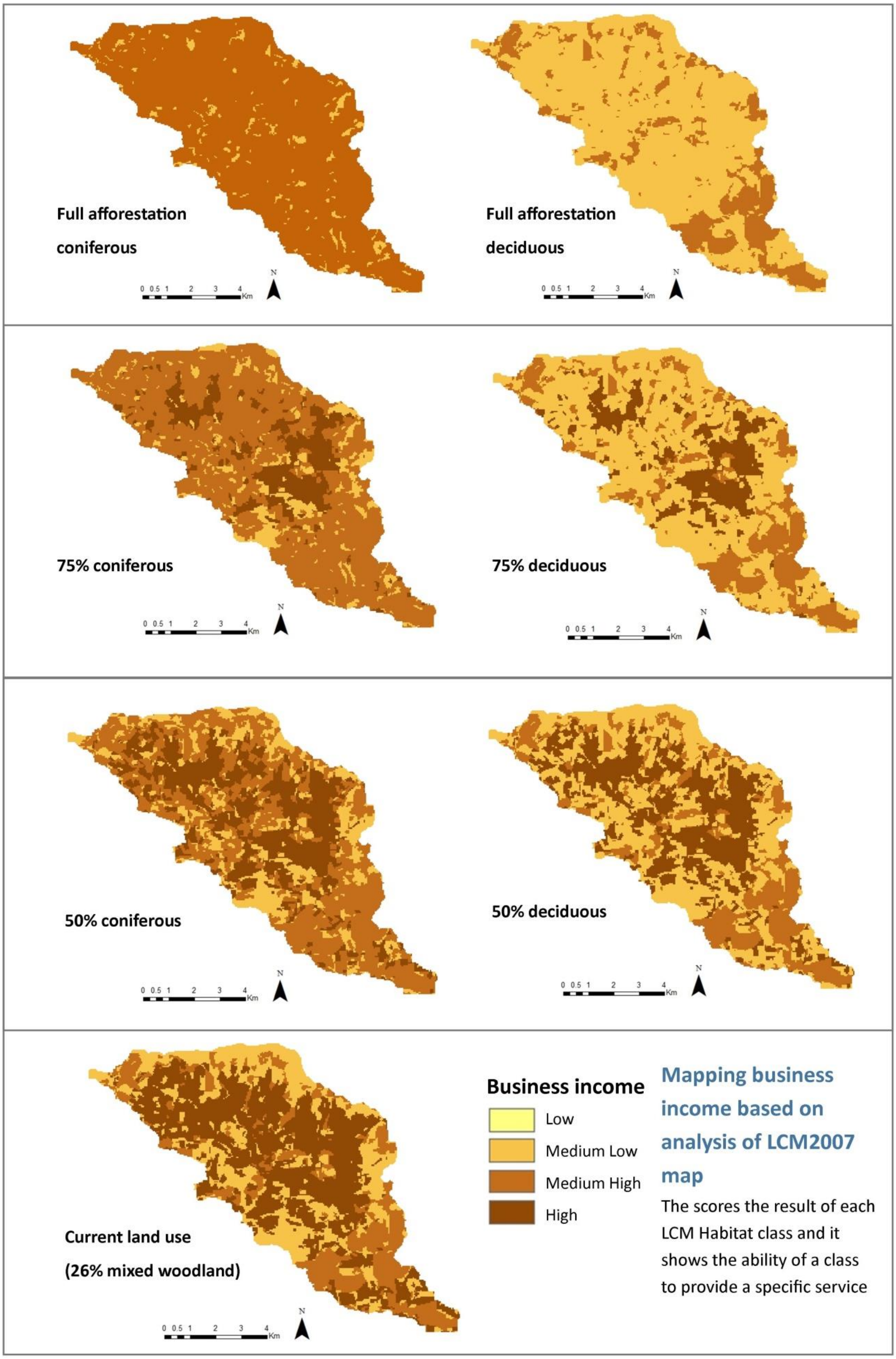
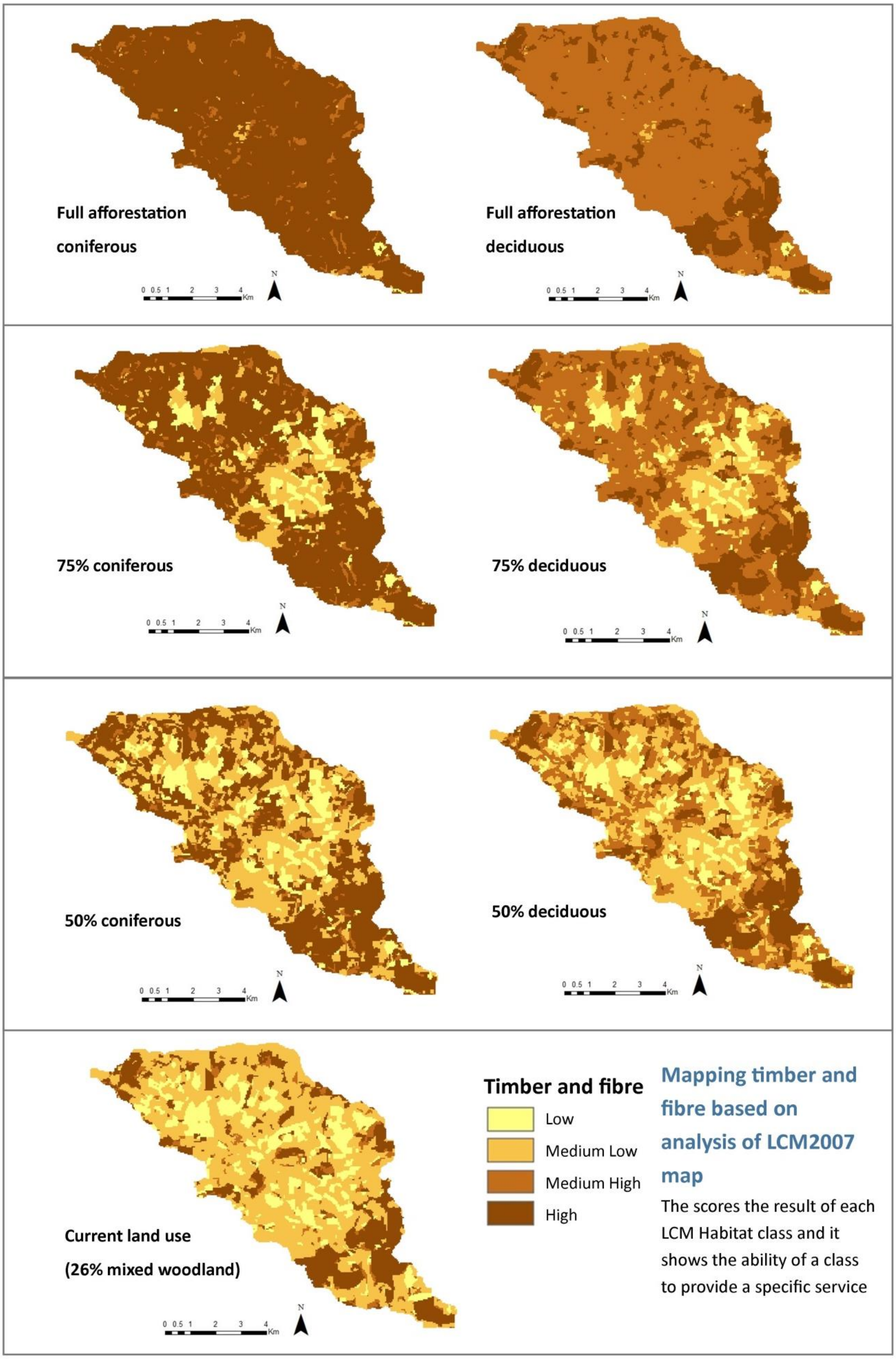


Figure A3.125. Design rainfall events for 15 hour duration event with winter profile for the 2080s

Appendix D

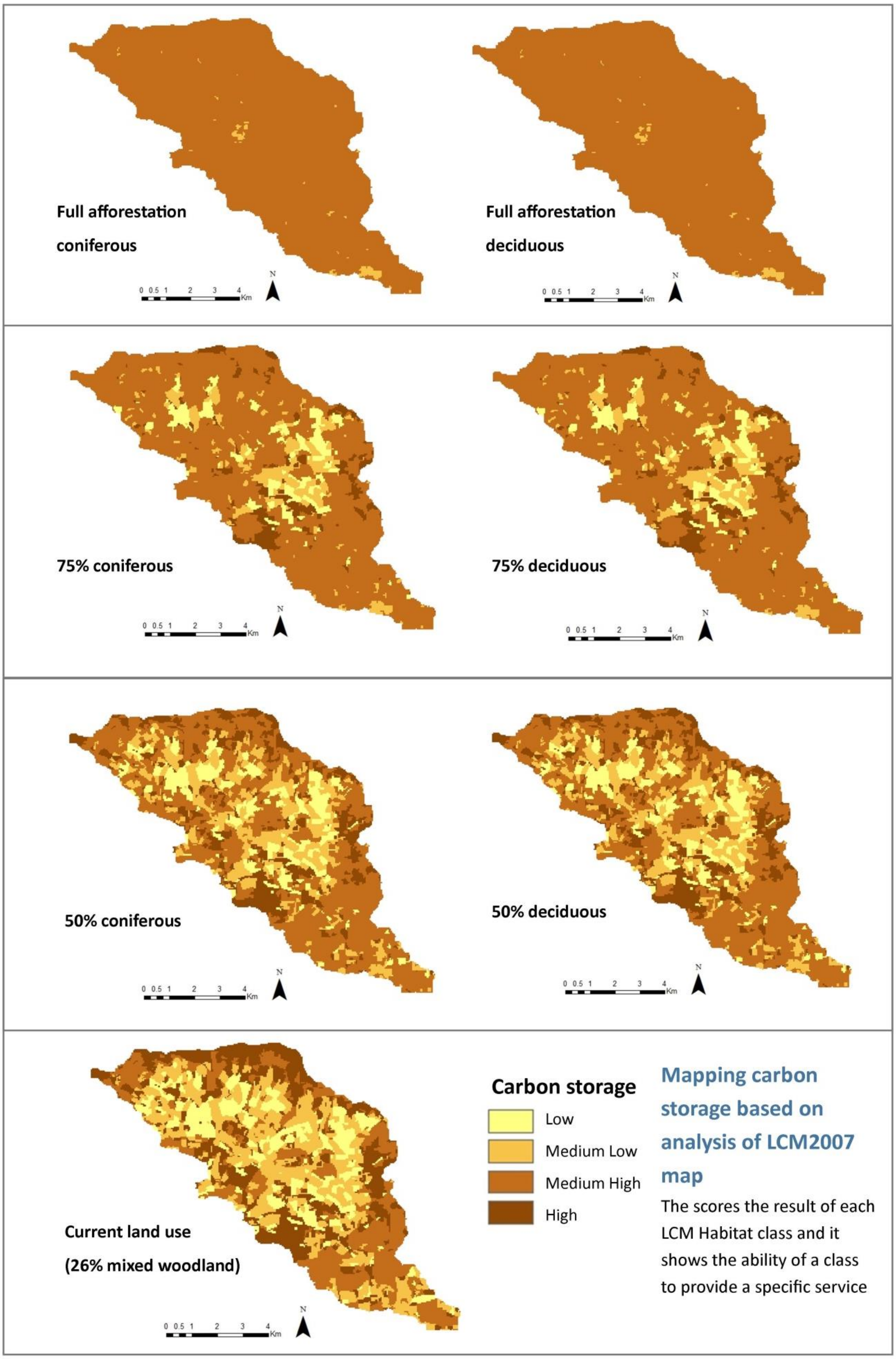

Full afforestation
coniferous
Full afforestation
deciduous
75% coniferous
75% deciduous
50% coniferous
50% deciduous
Current land use
(26% mixed woodland)
Food production
Low
Medium Low
Medium High
High
Mapping food production based on analysis of LCM2007 map
The scores the result of each LCM Habitat class and it shows the ability of a class to provide a specific service


Full afforestation
coniferous
Full afforestation
deciduous
75% coniferous
75% deciduous
50% coniferous
50% deciduous
Current land use
(26% mixed woodland)
Business income
Low
Medium Low
Medium High
High
Mapping business income based on analysis of LCM2007 map
The scores the result of each LCM Habitat class and it shows the ability of a class to provide a specific service



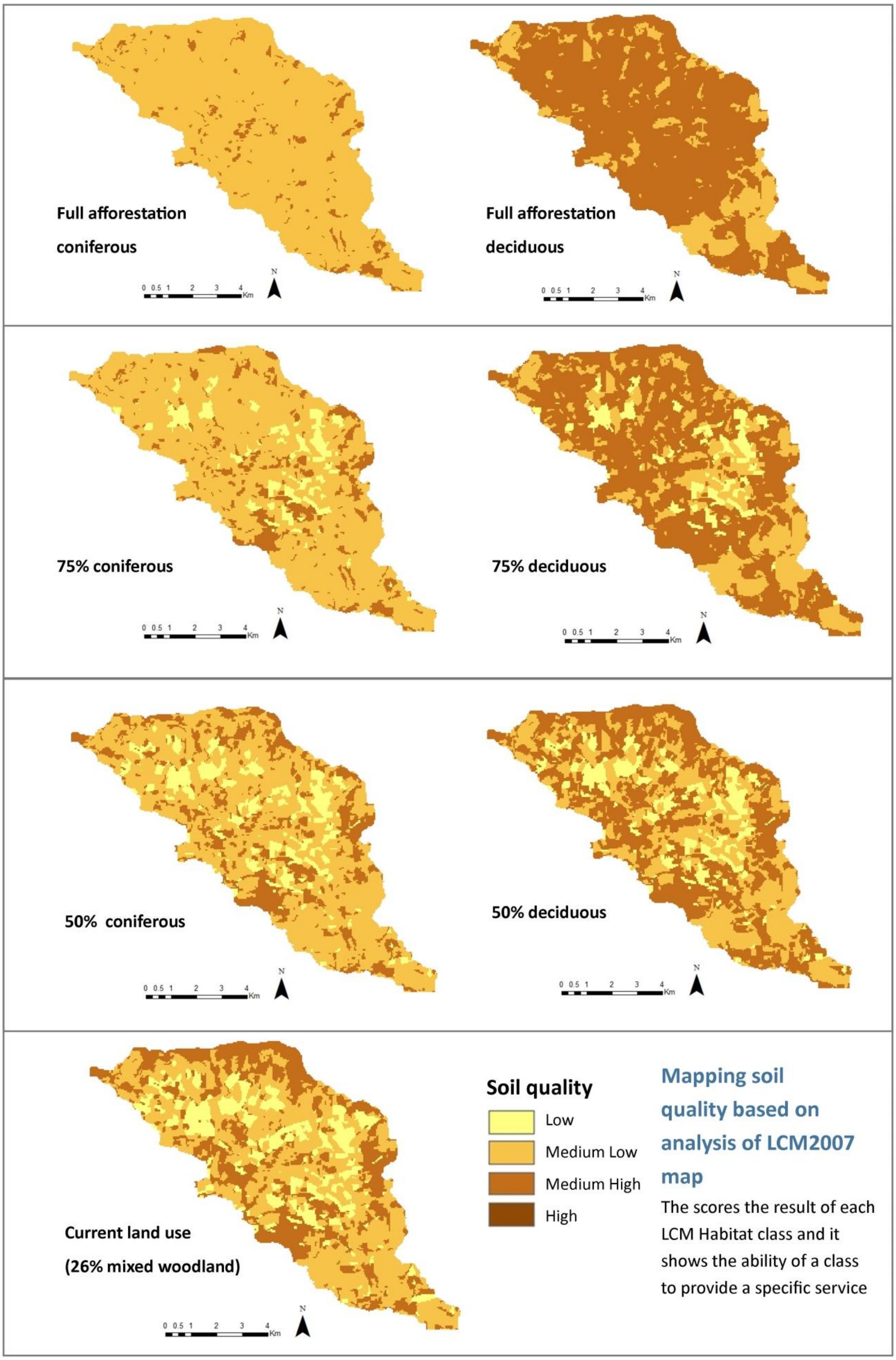
Mapping timber and fibre based on analysis of LCM2007 map

The scores the result of each LCM Habitat class and it shows the ability of a class to provide a specific service



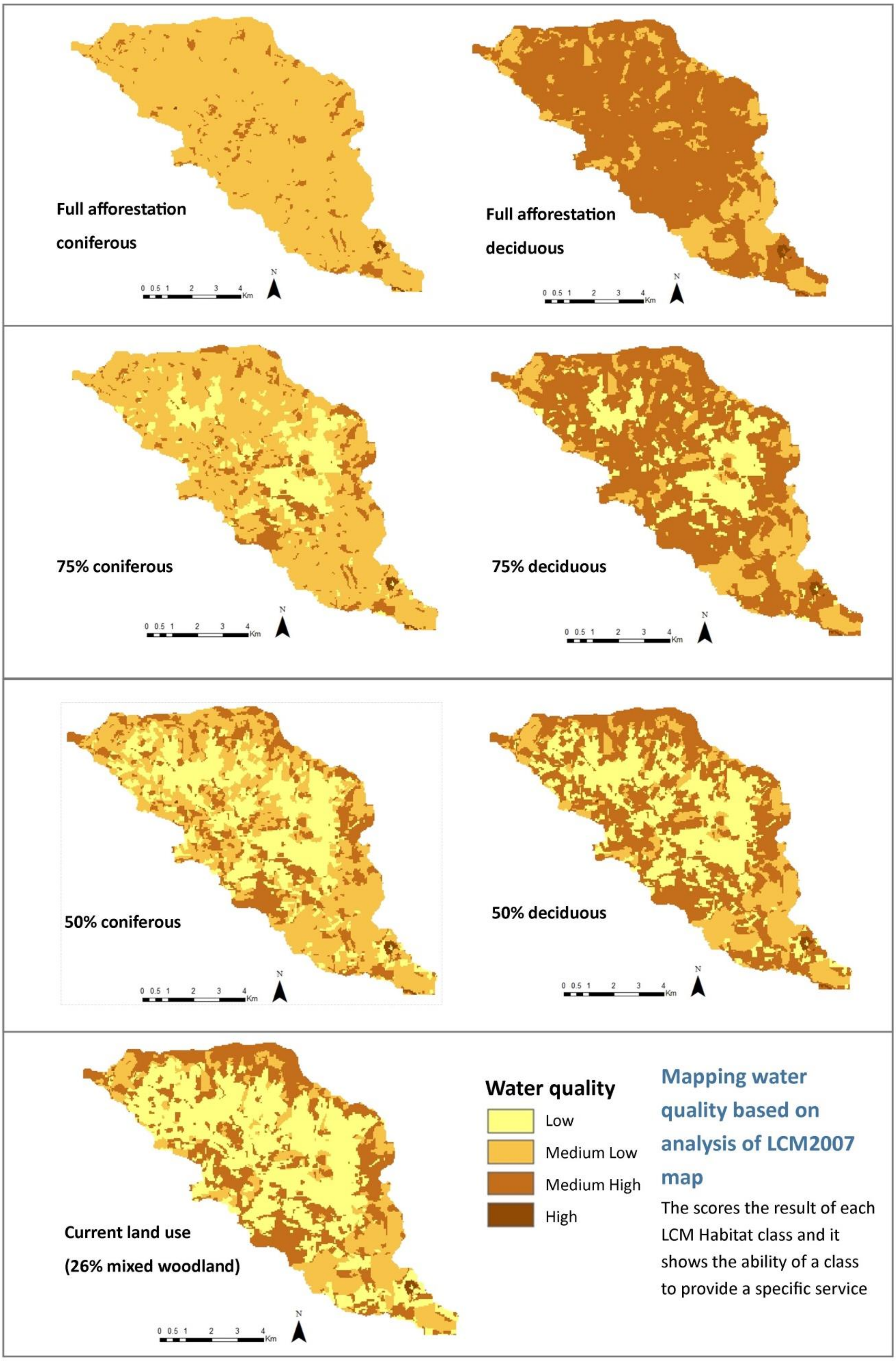
Mapping carbon storage based on analysis of LCM2007 map

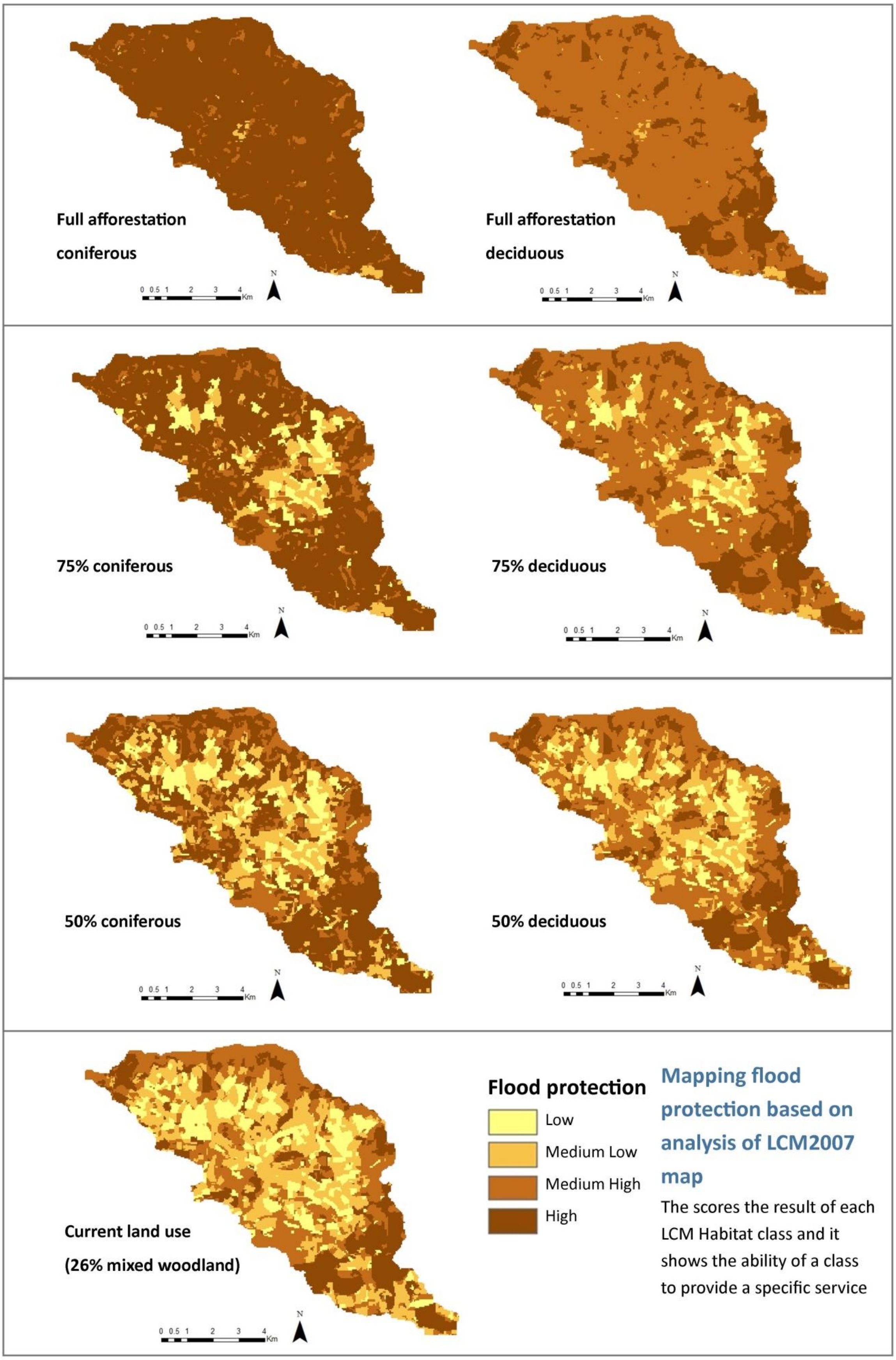
The scores the result of each LCM Habitat class and it shows the ability of a class to provide a specific service



Mapping soil quality based on analysis of LCM2007 map

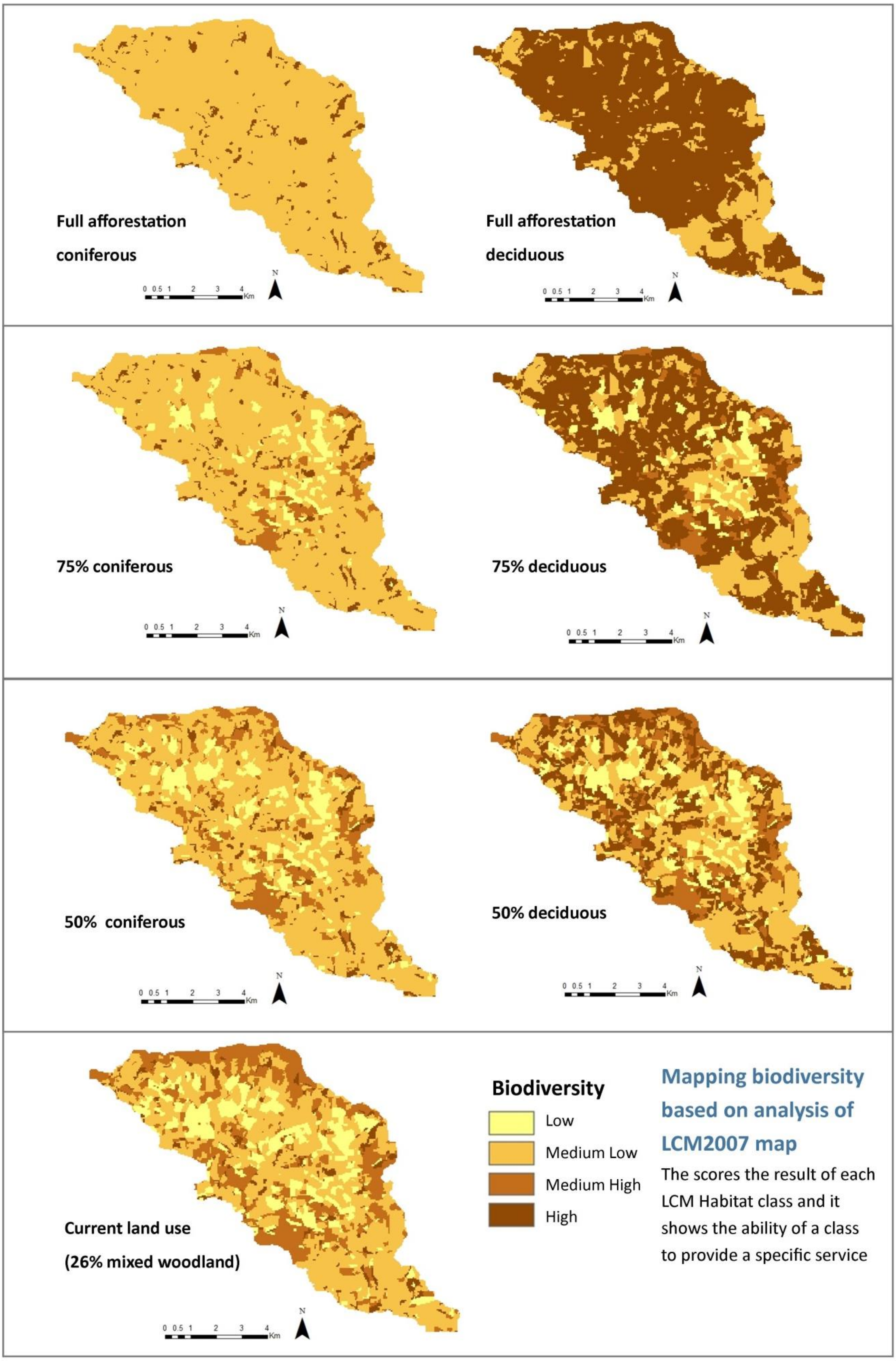
The scores the result of each LCM Habitat class and it shows the ability of a class to provide a specific service

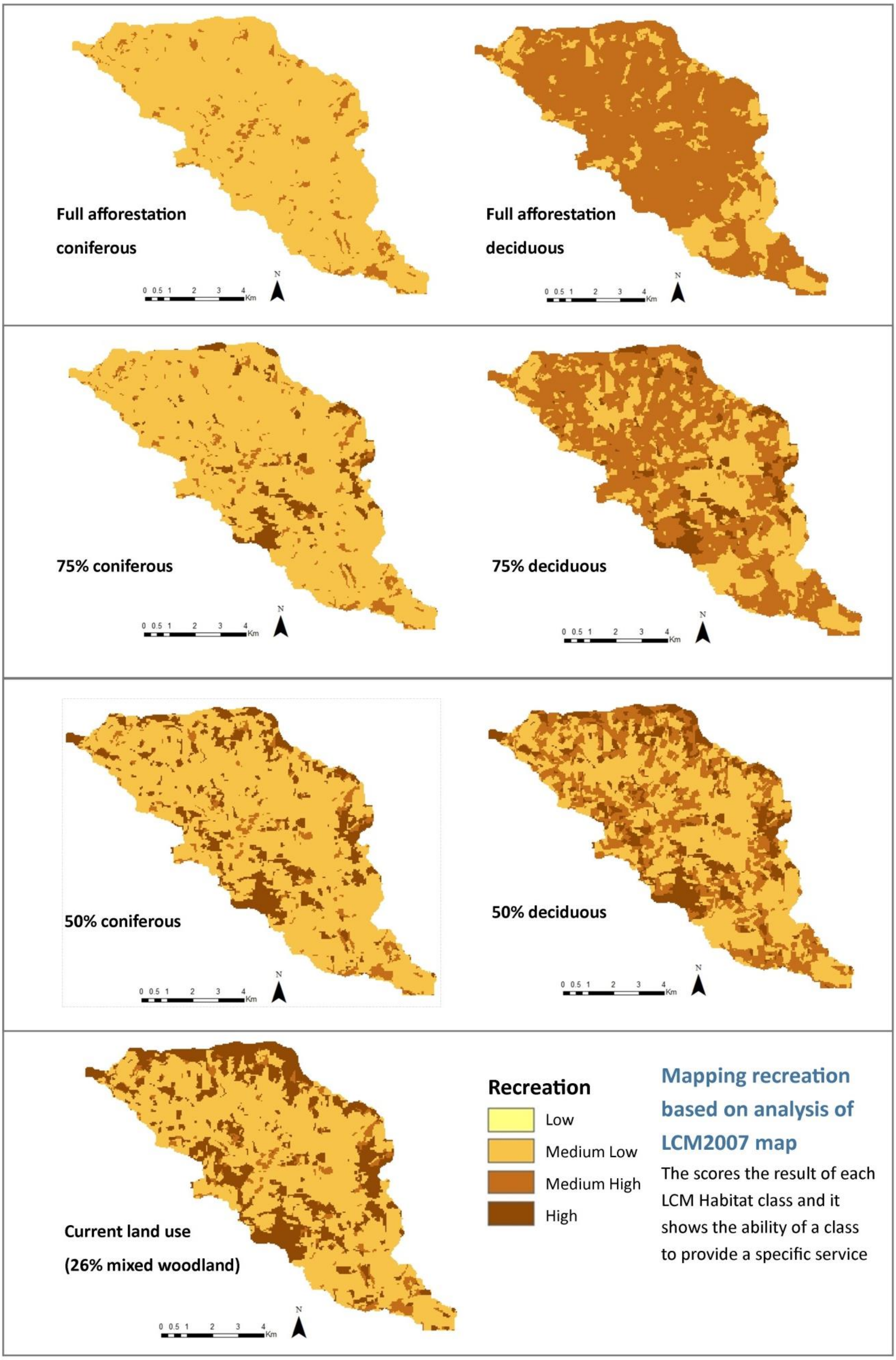

Full afforestation
coniferous
Full afforestation
deciduous
75% coniferous
75% deciduous
50% coniferous
50% deciduous
Current land use
(26% mixed woodland)
Water quality
Low
Medium Low
Medium High
High
Mapping water quality based on analysis of LCM2007 map
The scores the result of each LCM Habitat class and it shows the ability of a class to provide a specific service



Mapping flood protection based on analysis of LCM2007 map

The scores the result of each LCM Habitat class and it shows the ability of a class to provide a specific service


Full afforestation coniferous
Full afforestation deciduous
75% coniferous
75% deciduous
50% coniferous
50% deciduous
Current land use (26% mixed woodland)
Biodiversity
Low
Medium Low
Medium High
High
Mapping biodiversity based on analysis of LCM2007 map
The scores the result of each LCM Habitat class and it shows the ability of a class to provide a specific service



Mapping recreation based on analysis of LCM2007 map

The scores the result of each LCM Habitat class and it shows the ability of a class to provide a specific service